# Whole Life Carbon Assessment of 60 buildings

*Possibilities to develop benchmark values for LCA of buildings*

Zimmermann, Regitze Kjær; Andersen, Camilla Marlene Ernst; Kanafani, Kai; Birgisdottir, Harpa

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# PREFACE

Sustainability is increasingly a key concept in the debate on quality assurance of buildings. Sustainability within construction is about the environmental, economic and social quality of buildings, and is therefore considered a supplement to traditional qualities of a building.

There is extensive focus on finding solutions to reduce the carbon footprint of society. This also applies to buildings and the construction industry as a whole. For a number of years, the construction industry has been using life cycle assessment (LCA) to document the environmental impact of buildings. In order to carry out an LCA of buildings, proper documentation of the environmental impact of all materials used is necessary. In addition to documenting the environmental impact of materials, we are looking for different sustainable solutions to minimise the environmental impact and resource pressure of buildings.

The Danish Transport, Construction and Housing Authority has asked the Danish Building Research Institute (now BUILD - The Department of the Built Environment, referred to as BUILD below) to carry out a number of projects as part of the increased focus on environmental sustainability, including the development of LCAbyg, a Danish LCA tool for buildings, launched in 2015. After a number of years of building competencies and compiling experience within LCA, it is now possible to take the next step and examine how the environmental impact of buildings can be reduced. This can be done by generating knowledge about the environmental impact of buildings and by developing benchmark values for LCA of buildings that can be used for legislation, common sector guidelines, DGNB certification or tender documents, for example.

The purpose of this report is to establish a more extensive knowledge base about the whole life carbon assessment of buildings that can be used to develop benchmarks values for buildings.

The report was prepared by BUILD in 2019 on behalf of the Danish Transport, Construction and Housing Authority. The report was prepared by Regitze Kjær Zimmermann, Camilla Ernst Andersen, Harpa Birgisdottir and Kai Kanafani. Before publication, the script was peer-reviewed by Morten Birkved, professor with special responsibilities at the University of Southern Denmark. BUILD is grateful for the constructive collaboration with Professor Morten Birkved.

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# SUMMARY

Globally, the building and construction sector is responsible for approx. 39% of all Green House Gas emissions, and approx. 28% comes from operational energy use for the total existing building stock and approx. 11% comes from consumption of materials for new buildings and refurbishment of existing buildings (World Green Building Council, 2019). Whole life carbon emissions (Global Warming Potential, GWP) and other environmental impacts from both operational energy use and from building materials can be determined and reduced using life cycle assessments (LCA).

In Denmark, the Danish Transport, Construction and Housing Authority and The Department of the Built Environment (BUILD) have developed a tool to carry out LCA of buildings, LCAbyg, and have published a number of Danish publications about LCA of buildings. In practice, LCA has been used in the DGNB certification system for buildings since 2012. Data from all these LCAs has not previously been collected and calculated according to a uniform method. Therefore, there is still a lack of broad understanding of the current level of environmental impacts from buildings. In addition, the DGNB does not yet include detached houses, accounting for a significant percentage of building activities in Denmark.

This report presents LCAs of 60 building cases built from 2013 to 2021. The case buildings come from DGNB-certified projects, external projects and life cycle assessments carried out by BUILD. The cases are divided into five building types focusing on homes and offices, see figure 1. When collecting the case buildings, attempts were made to include a broad selection of cases with different qualities in terms of building types, energy classes, materials, photovoltaic area, etc. This takes into account the differences between buildings, so that the data basis for the benchmark values is as representative as possible.

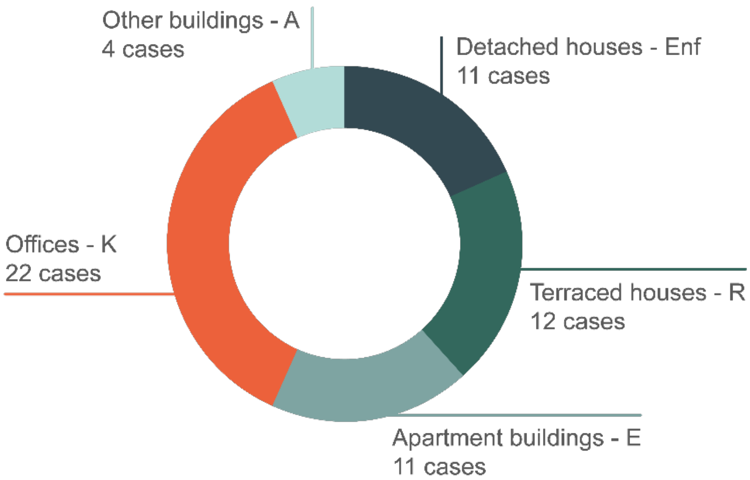



**FIGURE1.** Number of cases by building type. There are 60 cases in total, 34 of which are homes and 26 are offices and other buildings – including a school, a hospital and multi-functional buildings.

The life cycle perspective from the LCA includes upfront carbon emissions, i.e. production of building materials, as well as impacts expected to take place on the basis of a future scenario related to replacements, operational energy and demolition. The calculations were made in LCAbyg with the associated calculation method and environmental database. Results of the LCAs of all case buildings can be seen as bars in figure 2 for a 50-year reference study period and an 80-year reference study period, respectively. The 50-year reference study period is most widespread and in line with the European Level(s) reporting framework. The results show large variations in the impacts of buildings, as some buildings have up to 2.25 times greater impacts than others in a 50-year reference study period and up to 2.5 times greater impacts than others in an 80-year reference study period.

The impacts of the buildings can be divided into impacts from materials (referred to as embodied impacts) and impacts from operations. Impacts from materials are approx. 2-4 times greater than impacts from operations for a 50-year as well as an 80-year reference study period. Furthermore, there is a large gap between impacts from materials alone, varying from 3.7 to 10.8 kg $CO_2$ eq/m$^2$/year at 50 years and 3.11 to 9.50 kg $CO_2$ eq/m$^2$/year at 80 years. The same applies to impacts from operational energy use, varying from 0.22 to 4.58 kg $CO_2$ eq/m$^2$/year at 50 years and 0.17 to 4.30 kg $CO_2$ eq/m$^2$/year at 80 years. Results also show that there is not a big difference in impacts for the GWP of different building types, neither in impacts for operational energy nor materials. The median value for the GWP of materials for detached houses, terraced houses, apartment buildings and offices is (7.4) (7.1) (7.0) and (6.9) kg $CO_2$ eq/m$^2$/year in a 50-year reference study period, respectively.

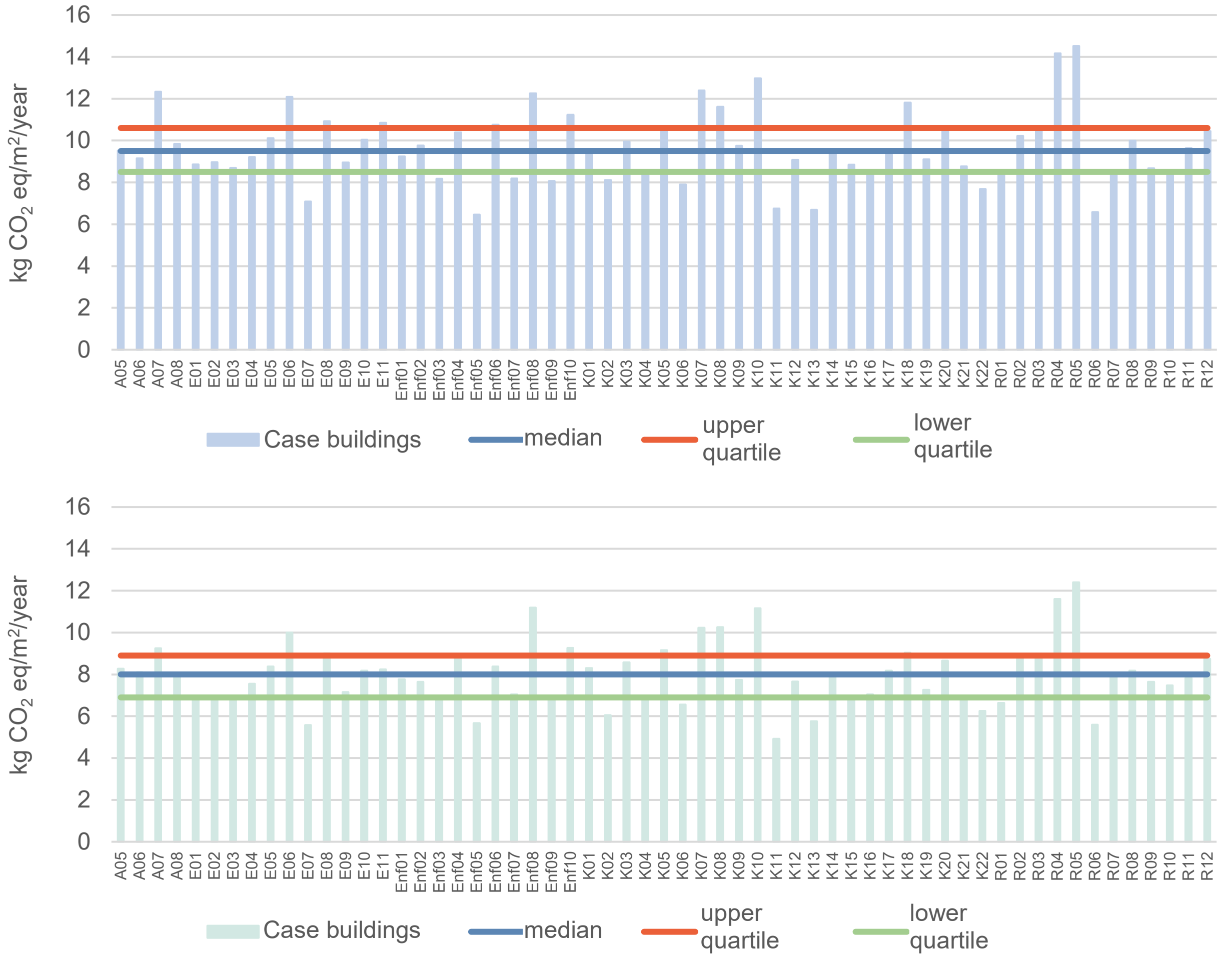



**FIGURE 2.** GWP and benchmark values of case buildings GWP is shown per square metre of gross floor area and year over a 50-year reference study period (top) and an 80-year reference study period (bottom).

The LCA results can be used to establish a common basis for the environmental performance of buildings by means of benchmark values. A common benchmark value can form the basis for tender requirements, public regulation or other types of benchmarking that already exist for energy demand, indoor climate or other areas, but are missing for the life-cycle-based environmental impact in Denmark. Work on preparing an LCA can be facilitated by carrying out an estimated LCA. Annex III illustrates how the LCAbyg functions for an estimated LCA can be used to give a conservative estimate of the environmental impacts of buildings.

The results of the LCAs are included in a statistical analysis to determine the benchmark values on the basis of the 60 case buildings. The benchmark value is then expressed as the median, upper and lower quartile for a 50-year and an 80-year reference study period, respectively, each of which suggests a possible level of ambition. The median and quartiles are shown as horizontal lines in figure 2. The median value for the 50-year reference study period is 9.5 kg $CO_2$ eq/m$^2$/year, while the lower quartile is 8.5 kg $CO_2$ eq/m$^2$/year. However, the median value for the 80-year reference study period is 8.0 kg $CO_2$ eq/m$^2$/year, while the lower quartile is 6.9 kg $CO_2$ eq/m$^2$/year.

The figure also shows that several buildings range considerably below the lower quartile in both a 50-year and an 80-year reference study period. These buildings, with impacts below the lower quartile, can therefore also be included as benchmarks for buildings of the future. Results for the individual case buildings are in Annex IV.

The benchmark values in this report correspond to a bottom-up approach based on the performance of existing buildings. The 60 cases in this report represent the largest number of LCAs of buildings collected in Denmark to date. Furthermore, they have been compiled in the same calculation tool, LCAbyg, and are therefore based on the same environmental data and the same method of calculation. Variation in building type, materials, etc. also means that the data represents a broad selection of buildings in Denmark. This provides a sufficient basis for preparing benchmark values for voluntary schemes. The benchmark values should be updated as more LCAs of buildings become available.

# CONTENTS

# 1 INTRODUCTION

## 1.1 Background

In recent years, interest in reducing anthropogenic impacts on the environment has increased, and the sustainable transition is now firmly on the agenda. Sustainability has social, economic and environmental aspects, the latter being the focus of this report. Sustainability is also considered an import aspect within the building and construction sector, and is increasingly an element in the quality assurance of buildings. As part of this development, the DGNB certification system was introduced in 2012 by the Green Building Council Denmark. In 2014, a voluntary sustainability class in the Building Regulations was proposed in the building policy strategy (Danish Ministry of Climate, Energy and Building, 2014).

There is extensive focus on finding solutions to reduce the climate footprint of society. The Danish government has set a goal to reduce GWP by 70% in the period from 1990 to 2030. This entails focus on identifying reduction possibilities in all corners of society, and the government has entered into a climate partnership with the business community in this respect.

The building and construction sector consumes a large percentage of the world's resources and contributes to negative impacts on the environment in the form of materials and energy use as well as generation of large volumes of waste. Globally, the building and construction sector is responsible for approx. 39% of all GWP, and approx. 28% comes from operational energy use for the total existing building stock and approx. 11% comes from consumption of materials for new buildings and refurbishment of existing buildings (World Green Building Council, 2019).

Generally, these environmental impacts can be brought down by reducing impacts from building materials and from the operation of buildings. For many years, Denmark has focused on reducing impacts from operational energy use by regulating requirements for energy demand in the Danish Building Regulations. This means that new buildings now have lower environmental impacts from operational energy use than from building materials, and therefore it is worth focusing on the environmental impact of building materials (Birgisdóttir & Madsen, 2017).

Environmental impacts and resource use from both operation and building materials can be determined in an LCA of a building. Using an LCA, environmental impacts for a given building can be quantified and compared with similar buildings to assess how the environmental impacts can be reduced. In DGNB certification, LCA has been an important part of assessing environmental sustainability since 2012. The certification system is based on benchmark values for LCA that the building must comply with. Initially, German benchmark values were adapted and used as reference for the first Danish DGNB certifications. As Danish experience in carrying out LCA of buildings grew, Danish benchmark values were developed (Rasmussen, et al., 2019) (Rasmussen & Birgisdóttir, 2018). In Denmark, benchmark values from DGNB have been used for LCA of buildings for about eight years, and they have been the largest source of Danish experience with LCA of buildings.

The proposed voluntary sustainability class in the building policy strategy from 2014 also included guidance efforts. Among other things, this meant that work was initiated to operationalise the LCA of buildings. Consequently, the LCA tool, LCAbyg, was launched in 2015, and since then various Danish publications on this area have been published, including *Introduction to LCA of Buildings* (Birgisdottir & Rasmussen, 2015), *LCA of Large Building Renovation* (Birgisdottir & Rasmussen, 2015) *Buildings' Embodied Energy and Environmental Impacts* (Birgisdóttir & Madsen, 2017) and *Early Design Stage Building LCA* (Kanafani, Zimmermann, Birgisdóttir, & Rasmussen, 2019). These publications and the growing number of LCAs of Danish buildings have helped form the current experience and basis for comparison, and this can be used to find the right level of reduction in the GWP of buildings.

France, Finland and Sweden are already developing national benchmark values for the carbon footprint of buildings. Moreover, several countries are considering introducing benchmark values in their building regulations to regulate GWP. The Netherlands is the frontrunner, and has had declaration requirements since 2013 and statutory requirements on compliance with a stipulated limit value since 2018. In parallel, an international standard for the methodology to set benchmark values is being prepared (ISO 21678) and Annex 72 under the International Energy Agency (IEA) is working to establish a common understanding of the environmental impacts of buildings (Frischknecht R., Birgisdottir, Chae, Lützkendorf, T., & Passer, 2019). So, many initiatives have been launched regarding benchmark values for LCA of buildings, all of which are intended to illustrate the need to minimise environmental impacts in order to achieve a more sustainable building and construction sector.

## 1.2 Purpose

The purpose of this report is to establish an adequate data basis on the GWP of buildings in Denmark throughout their life cycle. On the basis of this data, possible benchmark values adapted to the LCA method used in Denmark are outlined. BUILD has previously prepared benchmark values for LCA for use in DGNB certification, but the benchmark values in this report are based on a considerably larger data basis and an updated method.

The data basis was developed to carry out LCA of 60 Danish case buildings. The report analyses and interprets the results and outlines a selection of benchmark values for the GWP. The selection of benchmark values can be used to set requirements to minimise the GWP of buildings, e.g. in legislation, DGNB certification or tender documents.

## 1.3 Reading guide

The report is divided into an introduction, method, results and analysis, and it culminates in the last section outlining benchmark values:

*Chapter 2* of the report begins with a brief introduction to LCA of buildings.

*Chapter 3* presents the case buildings and the LCA method used as the basis to calculate the benchmark values.

*Chapter 4* presents the results from the LCAs on the selected case buildings over a 50-year reference study period. Possible benchmark values can be determined on the basis of these results.

*Chapter 5* presents the results from the LCAs on the selected case buildings over an 80-year reference study period. Possible benchmark values can be determined on the basis of these results.

*Chapter 6* analyses the results in relation to parameters that have proven to be important in an LCA. There are analyses of how these parameters affect the results of an LCA and the benchmark values over a 50-year reference study period.

*Chapter 7* outlines possible benchmark values for LCA of buildings for both a 50-year and an 80-year reference study period.

# 2 LCA OF BUILDINGS

LCA is a standardised method to assess potential environmental impacts and resource use of a building. The long-term perspective ensures that impacts from the full life cycle of the building are included, including the production of building materials, transport, installation, maintenance, replacements and processing of materials at the end-of-life stage and operational energy for the building, see figure 3. In practice, Denmark does not yet include all stages of the life cycle (modules included are marked in blue in figure 3). This is due to focus on the most environmentally important stages of the life cycle and a lack of experience and routines in documenting all other stages of the life cycle. This approach is also referred to as the simplified LCA in the European framework for sustainable buildings: Level(s). As experience grows and more LCAs of buildings become available, focus on including more life cycle stages is increasing – particularly the upfront stages such as the construction process stage.

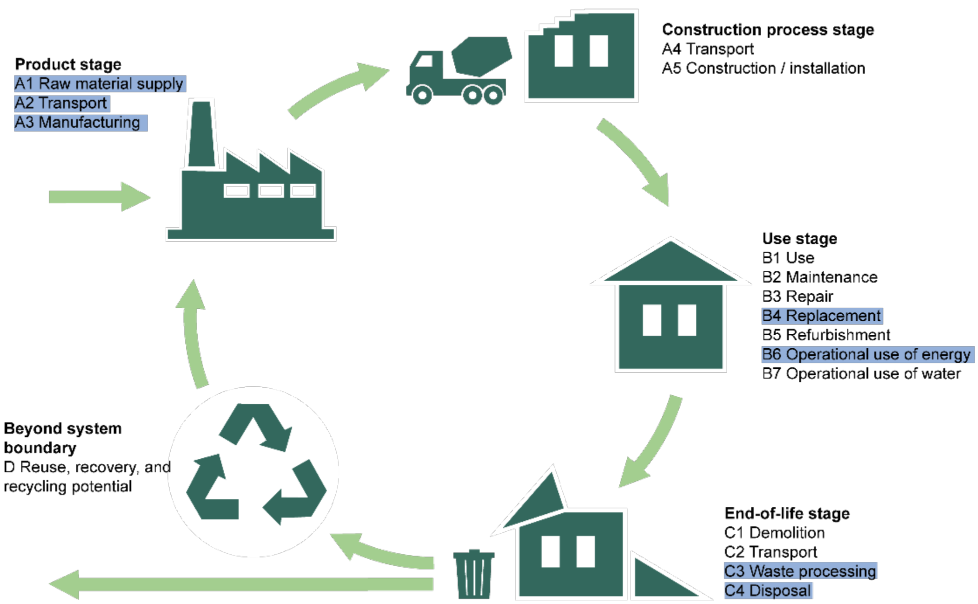



**FIGURE 3.** Stages (A, B, C and D) and modules (A1, A2, etc.) in the life cycle of a building. The LCA quantifies environmental impacts for the individual stages or modules. The sum of environmental impacts constitutes the environmental profile of the building. The common practice in Denmark is only to include the modules marked in blue.

Environmental impacts and resource use are calculated separately for each stage of the life cycle, and on the basis of a reference study period. This period is assumed to constitute the operation stage of the building. At the end of the reference study period, the building will be considered demolished to complete the life cycle perspective. However, the reference study period should not be compared with the expected service life of the building, which may be longer.

Impacts are normally stated within a number of environmental impact categories reflecting the different types of environmental damage. Denmark usually operates with the following categories:

– Global Warming Potential, GWP

– Depletion Potential of the Stratospheric Ozone Layer (ODP)
– Acidification Potential
– Eutrophication Potential
– Formation Potential of Tropospheric Ozone Photochemical Oxidants
– Abiotic Depletion Potential for Non-fossil Resources
– Abiotic Depletion Potential for Fossil Resources
– Total Use of Primary Energy
– Use of Renewable Secondary Fuels

If different environmental impact categories are to be used as one common benchmark value, this will require a decision on how these categories should be weighted against each other. This study focuses on GWP. GWP is an environmental impact indicator for the global warming potential of the earth's surface temperature on the basis of an increased concentration of greenhouse gases contributing to the greenhouse effect. The unit is kg $CO_2$ eq, where the various greenhouse gases are converted into the GWP of carbon dioxide.

The life cycle perspective includes upfront carbon emissions, i.e. production of building materials, as well as impacts expected to take place on the basis of a future scenario related to replacements, operational energy or demolition. This is illustrated in figure 4, in which the accumulated, i.e. combined, impacts are shown over a reference study period – here 50 years. The figure shows two curves: The upper curve relates to the impacts of materials, and the lower curve relates to impacts from operational energy.

Impacts from production of materials are seen in the large increase at year 0 of the upper curve. Building parts are replaced in the period between year 0 and year 50. The replacements result in impacts from disposal of the construction product and in impacts from production of a new, similar construction product. These impacts are seen as small and large increases on the upper curve. There are simultaneous impacts from operational energy as illustrated by the lower curve. At year 50, impacts are calculated up to the end-of-life stage of the building, corresponding to demolition of the building and disposal of all building materials. These impacts can be seen as an increase in the upper curve.

The life cycle perspective is important to avoid staggering impacts from one stage of the life cycle to another. However, it is also important to be aware of upfront carbon emissions, particularly because these impacts can be calculated with greater certainty, and a reduction of these would have a direct environmental effect.

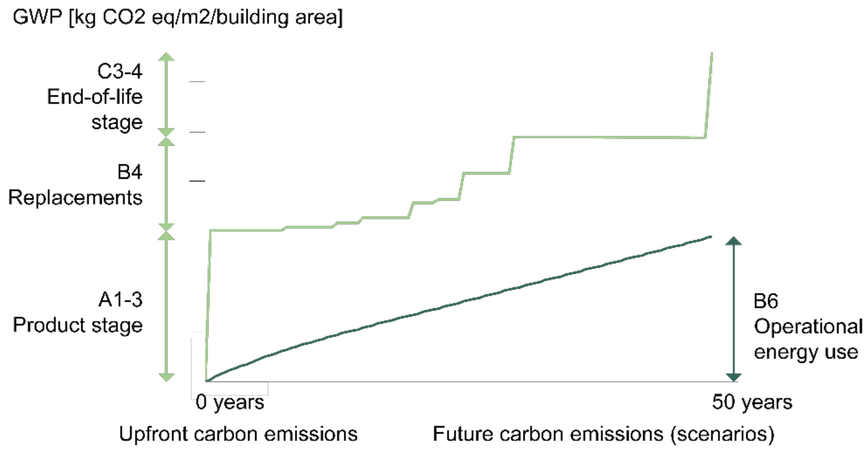



**FIGURE 4.** Accumulated impacts over the reference study period. The figure shows separate contributions from materials (upper curve) and operations (lower curve). The graph illustrates that buildings cause a significant impact from materials during construction (A1-3). Over a reference study period, there will be impacts from replacement of materials (B4) and energy use (B6). In connection with demolition, there are impacts from processing the materials at the end-of-life stage (C3-4).

# 3 CALCULATION BASIS

## 3.1 60 case buildings

The data used to prepare benchmark values comes from DGNB-certified projects, external projects and life cycle assessments carried out by BUILD as part of this project. A total of 60 different case buildings have been included, and these have been/will be built between 2013 and 2021. They are divided into five building types (see figure 5). Figure 5 also shows a code for each building type to make it easier to identify the building types included in the results in section 4, 0 and 6.

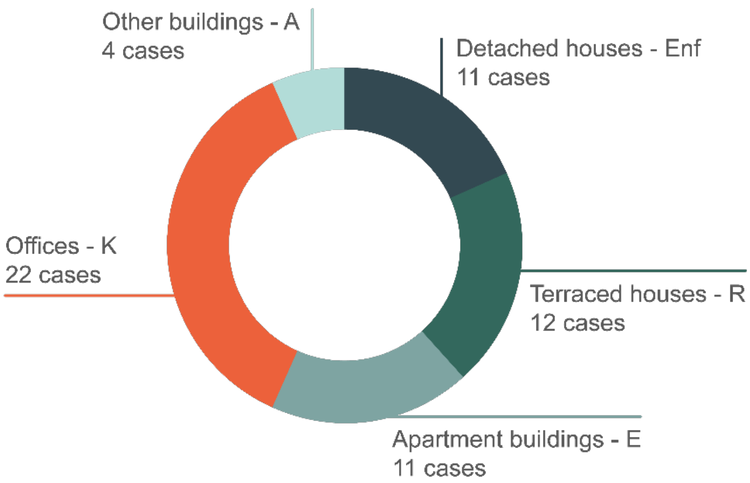



**FIGURE 5.** Number of cases by building type. There are 60 cases in total, 34 of which are homes and 26 are offices and other buildings – including a school, a hospital and multi-functional buildings.

Out of the 60 case buildings, 37 DGNB-certified projects have been included within the building types: *Terraced houses, Apartment buildings* and *Offices*. To ensure sufficient data and to include *Detached houses*, BUILD has carried out additional life cycle assessments of a number of projects. The assessments were based on material specifications from drawings obtained from architects, consultants and manufacturers of prefabricated houses. The remaining cases come from external projects obtained by BUILD. Among other things, the external projects concern buildings in the *Other buildings* category, and they include a school, a hospital and multi-functional buildings. When collecting the case buildings, attempts were made to include a broad selection of cases with different qualities in terms of building types, energy classes, materials, photovoltaic area, etc. This takes into account the differences between buildings, so that the data basis for the benchmark values is as representative as possible. However, no statistical assessment has been made of which case buildings are most representative of the Danish building stock.

As part of the data basis for the benchmark values, all projects are updated to LCAbyg version 4.0 (beta) in order to compensate for differences in the method and data base. This process ensures that all cases include the elements that LCAs should include according to EN15978, and that the database available in LCAbyg version 4.0 (beta) is the primary source of environmental data. LCAbyg version 4.0 (beta) is a beta version of the official LCAbyg version 3, and it is a calculation tool developed by BUILD and published by the Danish Energy Agency (now the Danish Transport, Construction and Housing Authority). The DGNB-certified projects have been transferred from DGNB's LCA tool to LCAbyg, where the external projects and BUILD projects have been updated from an older version of LCAbyg to LCAbyg 4.0 (beta).

Figure 6 describes the building types according to source, energy class, area and construction type, and the construction type is stated in two categories – heavy and light buildings. The differentiation between heavy and light buildings is related to the load-bearing structures, where heavy buildings have internal walls or concrete elements and light buildings have skeleton constructions. The differentiation is independent of the type of façade cladding used.

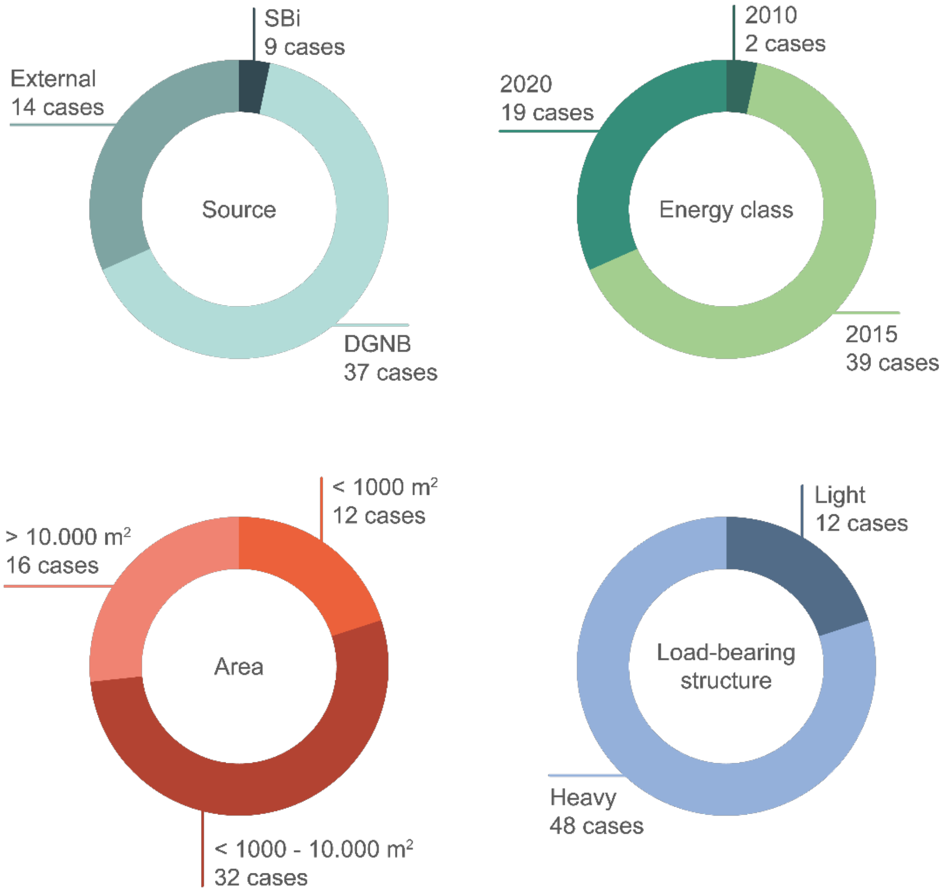



**FIGURE 6.** Summary of the data basis for the five building types. Heavy buildings are defined as having load-bearing structures with internal walls or concrete elements, while light buildings have load-bearing structures in skeleton constructions. See Annex I, table 8 for the distribution of the individual case buildings.

In order to create an overview of the primary materials in the cases, the materials for all case buildings have been examined and categorised within the following building parts:

- *Foundation*
- *Basement slab*
- *Slabs*
- *External walls – load-bearing structures*
- *External walls – façades*
- *Internal walls,*
- *Windows*

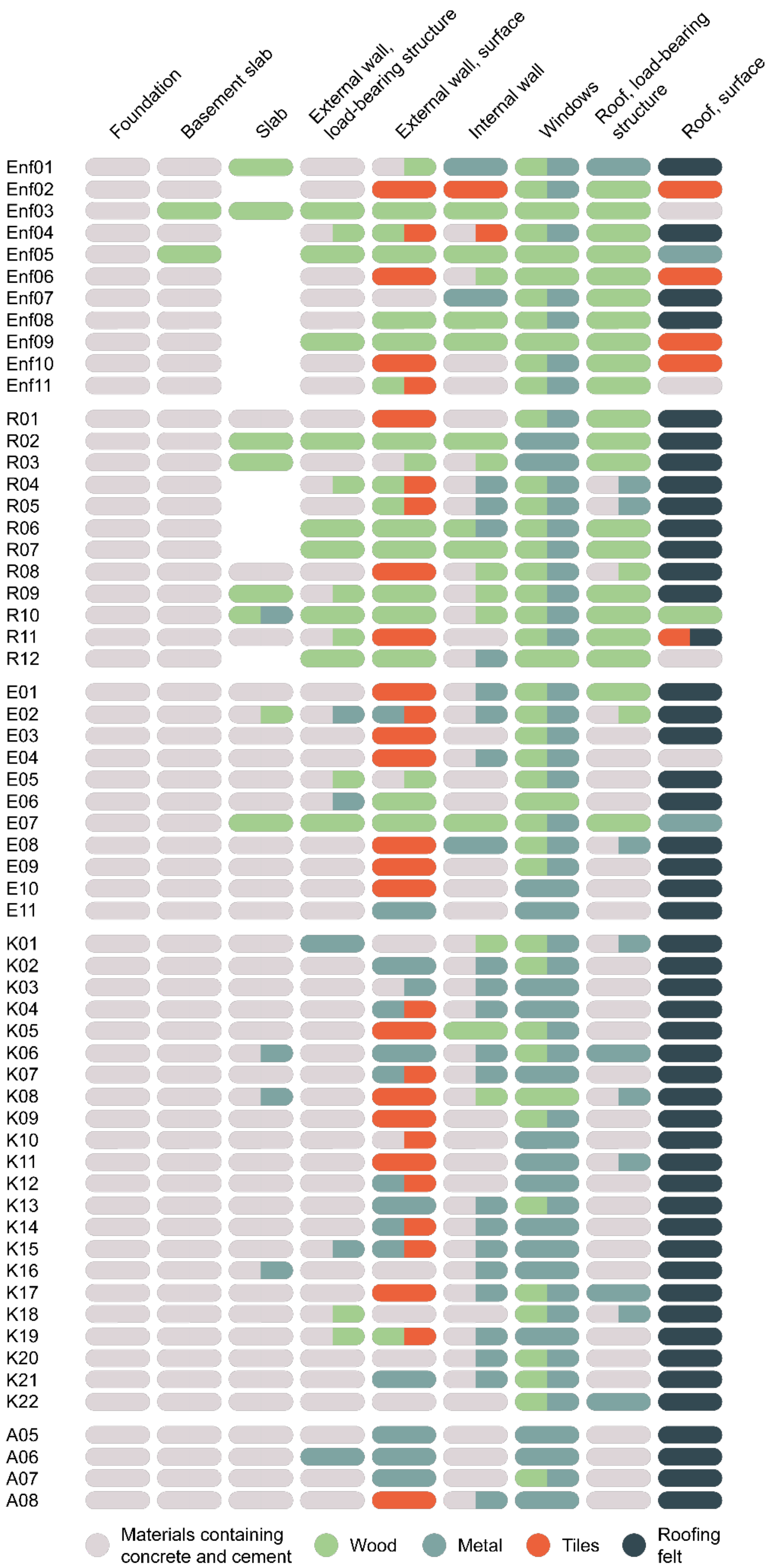
- *Roof – load-bearing structures*
- *Roof – surface*.

The *Internal walls* category includes both load-bearing and non-bearing internal walls, as it has not been possible to differentiate between these two categories. The materials have been further categorised into material groups covering the overall materials of the building. These tend to vary from building to building and can significantly influence the environmental impacts. The categories for materials within the various building parts are:

- *Materials containing concrete and cement*
- *Wood*
- *Metal*
- *Tiles* (bricks and roof tiles)
- *Roofing felt.*

Table 1 shows the distribution of materials in the case buildings.

**TABLE 1.** Summary of materials in the building parts for all case buildings



## 3.2 Methodology for LCA

**Life cycle stages**

According to the assessment of environmental performance of buildings standard, EN 15978, an LCA has five different life cycle stages and 17 underlying modules (see figure 7). Together, these make up the full life cycle of the building, taking into account consumption of building materials as well as processes regarding operation of a building (operational energy use and water use). In LCAbyg, it is currently only possible to calculate a selection of the 17 modules, i.e. production and transport of construction products (A1-3), replacement of building parts (B4), operational energy (B6) and waste processing at the end-of-life stage (C3-4). As LCAbyg version 4.0 (beta) has been chosen as the LCA tool to analyse the 60 case buildings, only the selected modules will be considered in this project. Figure 7 shows the modules included in EN 15978, as well as the modules covered by this project. See (Birgisdottir & Rasmussen, 2015) for a general introduction to LCA of buildings.

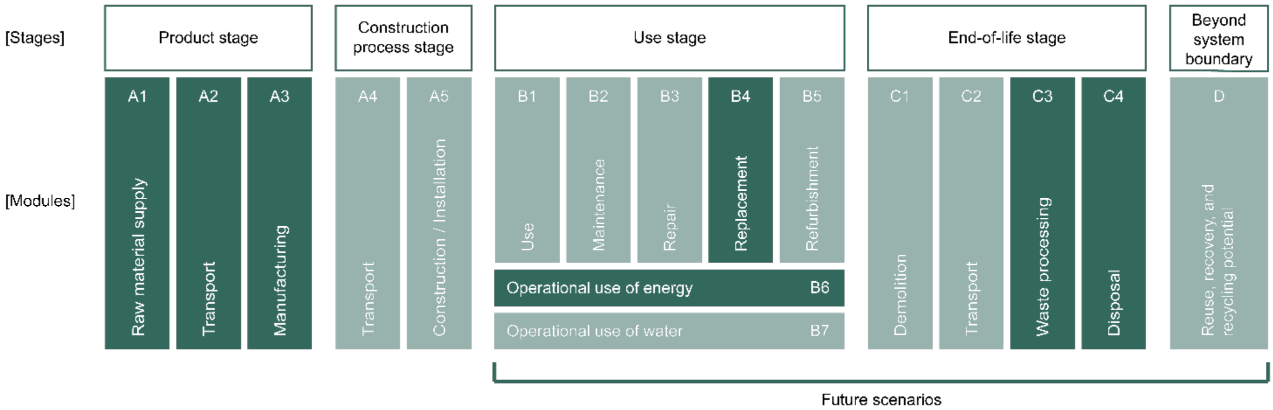



**FIGURE 7.** Life cycle stages in EN 15978. The modules available in LCAbyg and considered in this project are marked with dark green.

**Building parts included**

An LCA aims for as complete a picture of the building as possible. DGNB-certified projects generally follow the rules from DGNB in terms of which building parts to include in an LCA (DK-GBC, 2016). For external projects, completeness highly depends on the data available at the time of modelling. Danish Building Research Institute projects generally follow the SfB classification system for building parts, in which the following building groups are included if present in the building:

- Foundations
- Basement slabs
- Slabs
- External walls
- Load-bearing structures
- Internal walls
- Roofs
- Stairs/steps and ramps
- Balconies and access balconies
- Windows, doors and glass façades
- Drains
- Water
- Heating
- Ventilation and cooling
- Electricity and mechanical facilities
- Other

**Technical installations**

LCAs of buildings often lack data on technical installations. This also applies to the 60 case buildings in this report, where data for several groups of technical installations (drains, water, heating as well as ventilation and cooling) is missing for some of the case buildings. In some case buildings, these installations account for up to 10% of a building's GWP of materials (see Annex II, figure 27). As an incomplete building model could distort the result of the benchmark value, the results of the LCAs are adjusted for missing data on technical installations. Technical installations are pipes and installations included in the overall groups: drains, water, heating as well as ventilation and cooling. Photovoltaic modules are not included in technical installations, as there is sufficient data on photovoltaic modules. Therefore, it is not necessary to adjust the case buildings for missing data on photovoltaic modules.

Adjustment was made by replacing all case building data on the technical installations mentioned with generic data on technical installations. The generic data is based on the cases containing sufficient data on technical installations. The case buildings with sufficient data generate generic values (the median value) for the GWP for the different groups of technical installations. The median value for the different groups of technical installations is shown in table 2.

**TABLE 2.** Calculation of the representative GWP (median) for technical installations.

| Groups | Projects with completed group | Median value at 50 years [kg $CO_2$ eq/m$^2$/year] | Median value at 80 years [kg $CO_2$ eq/m$^2$/year] |
|---|---|---|---|
| **Drains** | 18% | 0.02 | 0.02 |
| **Water** | 23% | 0.12 | 0.11 |
| **Heating** | 37% | 0.23 | 0.24 |
| **Ventilation and cooling** | 30% | 0.08 | 0.08 |
| **Sum** | | **0.46** | **0.45** |

Note that the sum is calculated on the basis of the non-rounded values for medians. Therefore, the "Sum" row will not necessarily show the precise sum of the figures above.

**Reference study period**

A reference study period of 50 years and 80 years, respectively, is used for the LCAs of the 60 case buildings. Reference study period expresses the number of years the building is analysed in the LCA. The service life of the building can therefore be longer than the reference study period used. The longer the reference study period, the less the weight of the impacts during construction of the building. On the other hand, there will be greater weight on impacts in the use stage of the building, including replacement of materials and operational energy use.

During the start of the DGNB system, Denmark decided to use the same reference study period for LCA for certification as in DGNB Germany and internationally; i.e. 50 years. Later, when the DGNB manuals were updated, it was decided to use short reference study periods of 50 years and longer reference study periods of 80 years for offices, 100 years for schools, institutions and hospitals, and 120 years for homes, in line with Danish Building Research Institute report no. 30 from 2013(Aagaard, Brandt, Aggerholm, & Haugbølle, 2013) The reference study period of 50 years stems from financial depreciation periods of fixed asset investments, whereas the longer periods reflect expectations of the actual service life of buildings(Aagaard, Brandt, Aggerholm, & Haugbølle, 2013). An analysis of demolitions of 20,999

Danish buildings in the period 2009-2015 showed that the median value for the service life of the buildings was 59 years, and the average was 70 years (Østergaard, et al., 2018). The general European and international practices normally use reference study periods of 50 to 60 years. In the preliminary version of Level(s), it was slightly unclear whether to use 50 or 60 years for LCA (Dodd, Cordella, Traverso, & Donatello, 2017). The most recent announcement from Level(s) in February 2020 states that a reference study period of 50 years has been used in the updated version of Level(s). Table 3 shows reference study periods used in a comparative study of an office building carried out in the current international IEA Annex 72 project, which focuses on international harmonisation of LCA of buildings. Here, experts in 15 out of 21 countries used a reference study period of 50 years, 60 years in five out of 21 countries, and one country, i.e. Denmark, used a reference study period of 80 years. A comprehensive study of 650 scientific studies of LCAs of buildings shows that a reference study period of 50 years is used in approx. 60% of all studies (Röck, et al., 2020). Reference study periods of 80, 100 and 120 years are used in 9% of all studies.

The LCA results of the 60 case buildings have been examined for the significance of the reference study period in section 6.1.

**TABLE 3.** Reference study period used in an international comparative study of office buildings in the IEA Annex 72 project, which focuses on international harmonisation of LCA of buildings (Frischknecht R. , et al., 2019) (Frischknecht R., Birgisdottir, Chae, Lützkendorf, T., & Passer, 2019).

| | Belgium | Brazil | Canada | Denmark | France | The Nether- | Hong Kong | Italy | China | New Zealand | Norway | Switzerland | Portugal | Spain | United King- | Sweden | Czech Re- | Germany | Hungary | USA | Austria |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 50 | | x | | x | x | x | x | x | x | | | | x | x | x | x | x | x | x | x | x |
| 60 | x | | x | | | | | | | x | x | x | | | | | | | | | |
| 80 | | | | x | | | | | | | | | | | | | | | | | |

### Replacement of construction products

The reference study period affects the replacement of construction products. Construction products with a shorter service life than the reference study period must be replaced one or several times during the reference study period. In this project, service life for the individual building parts will be based on SBi-2013:30 and service life is also available in LCAbyg. The number of replacements depends on the service life determined for the individual construction products. In LCAbyg, it is assumed that construction products are only replaced if there are more than 10 years left of the reference study period and that construction products are not replaced if less than a third of the construction product's service life in the building is left.

### Database

Life cycle assessments in this project are primarily based on materials available in LCAbyg version 4.0 (beta). The database in LCAbyg for materials mainly consists of *generic* or *average* data from Ökobaudat 2016 and it only contains product-specific data to a limited extent. Ökobaudat is a German database and is therefore not necessarily representative of Danish production in relation to environmental impacts and resource use. There is currently no Danish database, and therefore it is not possible to use Danish data in the LCAs of buildings. This means there is a risk that Danish data has a higher or lower environmental impact than that calculated, and therefore it would be best to use Danish data to estimate the exact environmental impacts.

**Bio-based materials**

The database in LCAbyg includes biogenic carbon in bio-based materials. Bio-based materials can capture, store and release carbon in their lifetime. This carbon is referred to as biogenic carbon. The calculation of GWP for bio-based materials in the database in LCAbyg takes into account the capture and release of biogenic carbon, see EN 15804:2012. The standard states that GWP for bio-based materials should be calculated as negative in the product stage (modules A1-3) due to the capture of biogenic carbon during growth, and as positive at the end-of-life stage (modules C3-4) when the biogenic carbon is released in connection with decay or incineration. This means that the balance of biogenic carbon within the individual life cycle is calculated as 0. In this report, this means that case buildings containing large quantities of bio-based materials will typically have a low or negative GWP in the product stage and a high positive GWP at the end-of-life stage. Note that according to the latest version of the product standard (EN 15804:2012+A2:2019) the stored biogenic carbon should be reported separately from the carbon related to fossil fuels and the carbon related to changes in land use. This division is not yet available in the data forming the basis for the calculations in this report.

**Operational energy use**

Impacts from operational use for all case buildings are calculated on the basis of data available in LCAbyg. Data in LCAbyg is based on the report *Nye emissionsfaktorer for el og fjernvarme* (New emission factors for electricity and district heating) (COWI and the Danish Transport, Construction and Housing Authority, 2016). Projected data for the period 2015 to 2050 was chosen as a scenario in this project. This means that a gradual increase in the renewable energy share in the energy grid is expected during the given period (2015-2050).

**Environmental impact categories**

Results of these analyses are shown in LCAbyg for nine different environmental indicators, all of which are standard indicators in EN 15978. However, the purpose of this project is to focus on the environmental indicator *Global Warming Potential (GWP)*. This will therefore be the indicator in this report, and other indicators will be disregarded. The decision to focus on the GWP is based on the high priority of this topic today. An LCA will usually focus on several different environmental indicators in order to carry out a broad environmental assessment. It is essential to be aware of this, as other environmental indicators can be highly relevant and important if the full impact of a building is to be assessed.

**Reference unit**

Throughout the report, the results of LCAs will be presented in GWP, normalised to the area (per $m^2$) and the reference study period (per year). Normalisation to per $m^2$ is when the impact from operational energy use is normalised over the heated gross floor area, and where impacts from the materials are normalised over the gross floor area. Among other things, this is to avoid diluting the impacts from operational energy over an area larger than the area to be heated. Furthermore, the reference study period is used to normalise the results to ‘per year’.

**Data processing of results**

The results have undergone simple statistical data processing, in which the main focus was to examine differences in the 60 case buildings, and how these differences could affect the results in GWP and thus any benchmark value. Section 6 includes different aspects which have proven to have great influence on the GWP examined, including photovoltaic modules.

Relevant aspects for which the influence is not so well known have also been examined, including building type and design, energy class and secondary buildings. The results of how these aspects influence the environmental impacts will depend on the case buildings used in the analysis. Therefore, they cannot be considered as conclusions applying to all buildings. The aspects that have been examined more thoroughly are listed below.

- Reference study period
- Building type and design
- Photovoltaics
- Energy class
- Secondary buildings

Furthermore, Annex III examines how estimated LCAs can influence GWP. Estimated LCAs are often used in the early design stage, when the design has not yet been fully defined.

# 4 RESULTS FROM LCA IN A 50-YEAR REFERENCE STUDY PERIOD

## 4.1 Results from LCA of case buildings

This section shows the results of all case buildings in a 50-year reference study period in kg $CO_2$ eq/m$^2$ or kg $CO_2$ eq/m$^2$/year. The results are shown for all 60 case buildings, and adjustments have been made for missing data on technical installations, as described in section 3.2.

Figure 8 shows the impacts from the case buildings calculated over a 50-year reference study period and shown per m$^2$/year. The figure shows large variations in the total GWP of the buildings. Some buildings have up to 2.25 times greater impacts from both materials and operations than other buildings, varying from 6.45 to 14.52 kg $CO_2$ eq/m$^2$/year. Moreover, the figure shows that impacts from the building materials are typically 2-4 times higher than impacts from operational energy use. Impacts from materials vary from 3.67 to 10.84 kg $CO_2$ eq/m$^2$/year, whereas impacts from operational energy use vary from 0.22 to 4.58 kg $CO_2$ eq/m$^2$/year. In this context, it is important to note that the operational energy use for each building is based on data from energy performance framework calculations. The actual operational energy use is usually higher, because the calculation method does not cover all consumption and uses standard assumptions. This means that the actual GWP is likely to be higher.

Similarly, the actual GWP of materials will also be higher. The section on methodology states that not all life cycle stages have been included in the calculation. This means that the calculation does not include impacts from transport to the construction site as well as installation and material wasted on the construction site. Nor does it include repair and maintenance of building materials, which can also increase GWP.

Note that a single building (Enf11) has no data for operational energy use, and this building therefore has no impact on operations (see figure 8).

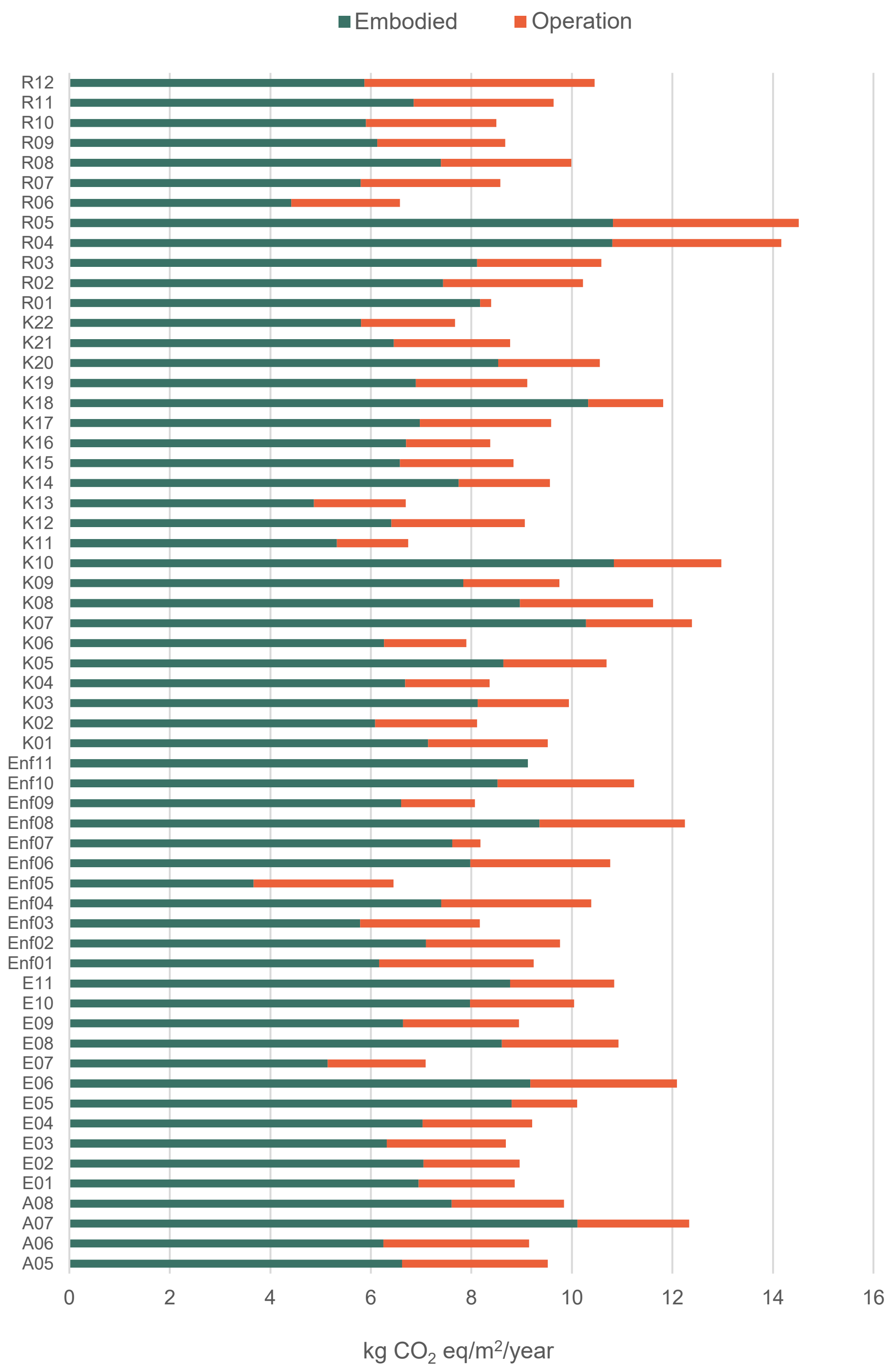



**FIGURE 8.** GWP of the 60 case buildings over a 50-year reference study period broken down by embodied carbon emissions (materials) and operational carbon emissions. Enf11 has no data for operations, and therefore only results for materials are shown.

Figure 9 illustrates how impacts from materials are distributed on an annual basis. The results are shown on a time axis in kg $CO_2$ eq/m$^2$, and it is clear that some impacts are upfront, whereas others are part of a future scenario. The figure shows that the GWP of materials for most buildings is highest in year 0 when the building is constructed. However, some buildings have a low impact in year 0, but a high impact in year 50 when the reference study period ends. This is because these buildings have a greater share of wood products which store biogenic carbon ($CO_2$). As described in section 3.2, it is assumed that this biogenic carbon will be released again at the end-of-life stage, where the release is included in the LCA regardless of whether the wood is assumed to be incinerated, reused or recycled. Buildings with a large share of biogenic material will therefore have a low or negative GWP in the product stage (modules A1-3) and a higher impact at the end-of-life stage (modules C3-4), which is also reflected in the results.

After upfront carbon emissions during construction of the building, replacement of materials (stage B4) is stated as impacts between year 0 and year 50. Figure 9 shows the that impacts from replacements happen in years 15, 20, 25 and 30, which usually corresponds to replacement of paint, roofing felt, double-glazed windows, photovoltaic modules and technical installations. However, material consumption in year 0 (modules A1-A3) will still typically result in the highest impact for most case buildings (see figure 10 to the left).

The figure also shows that, at the end of the reference study period in year 50, the total GWP of case buildings varies from 180 to 540 kg $CO_2$ eq/$m^2$ when only considering impacts from materials. This shows that there is a potential to reduce total impacts per $m^2$ via the selection of materials.

Figure 10 to the right shows that impacts from materials primarily come from the building part groups roofs, external walls and slabs/basement slabs. In some case buildings, there is no differentiation between slabs, basement slabs and roof slabs, which means that for some cases there are no impacts from Roofs, as impacts from the roof slab is categorised under Slabs etc. This is due to different choices in the LCA and these differences are particularly evident in DGNB-certified and external projects.

Moreover, figure 10 shows large impacts from the groups Windows, Internal walls, Foundations and Photovoltaic modules (where these are included). This indicates that the large building part groups make up the largest share of total impacts for the case buildings, and that this is where the greatest potential exists to reduce environmental impacts from buildings.

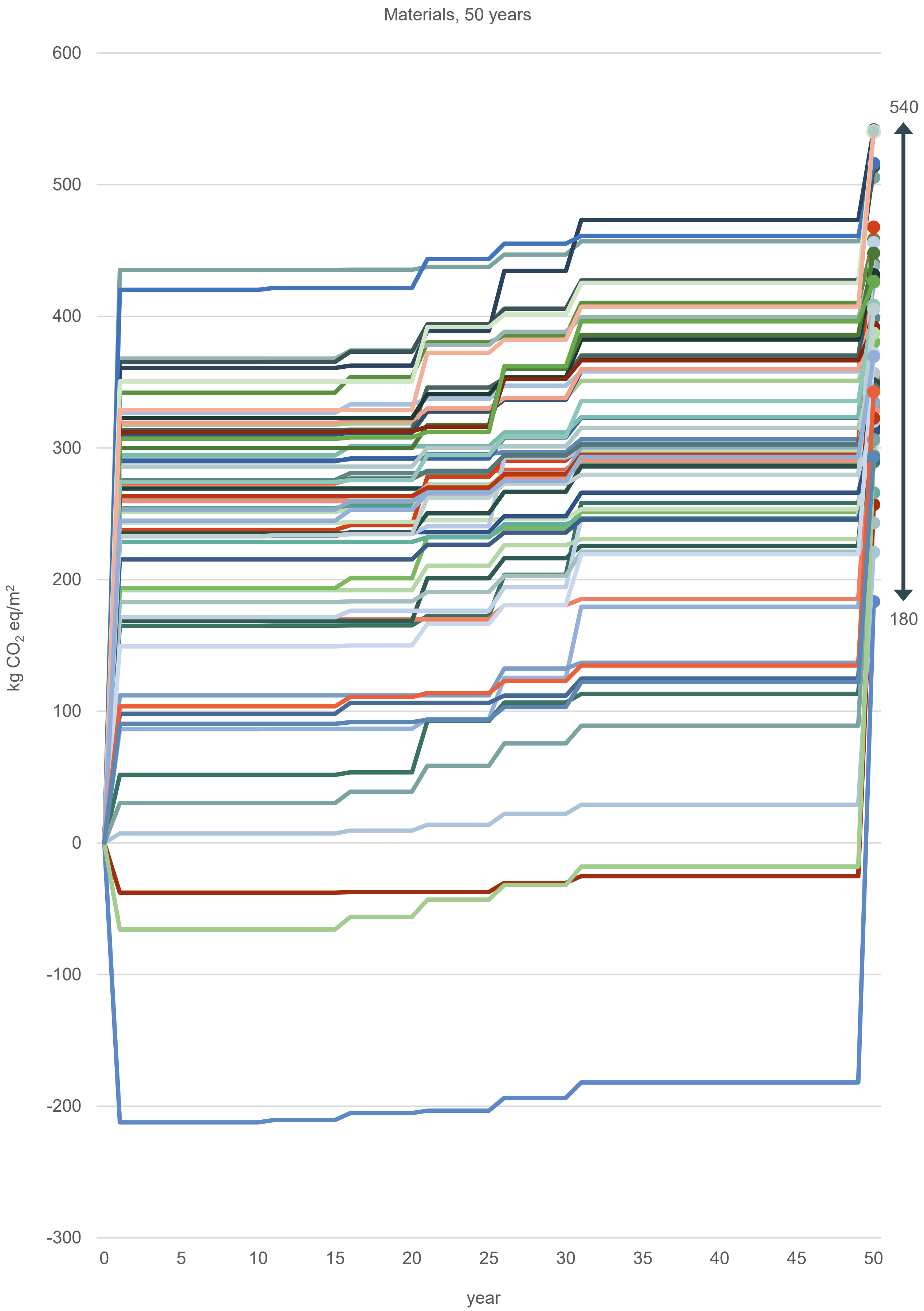



**FIGURE 9.** Accumulated GWP of case-building materials over a 50-year reference study period. GWP is stated per m$^2$ of gross floor area. GWP for operations is not included in the graph.

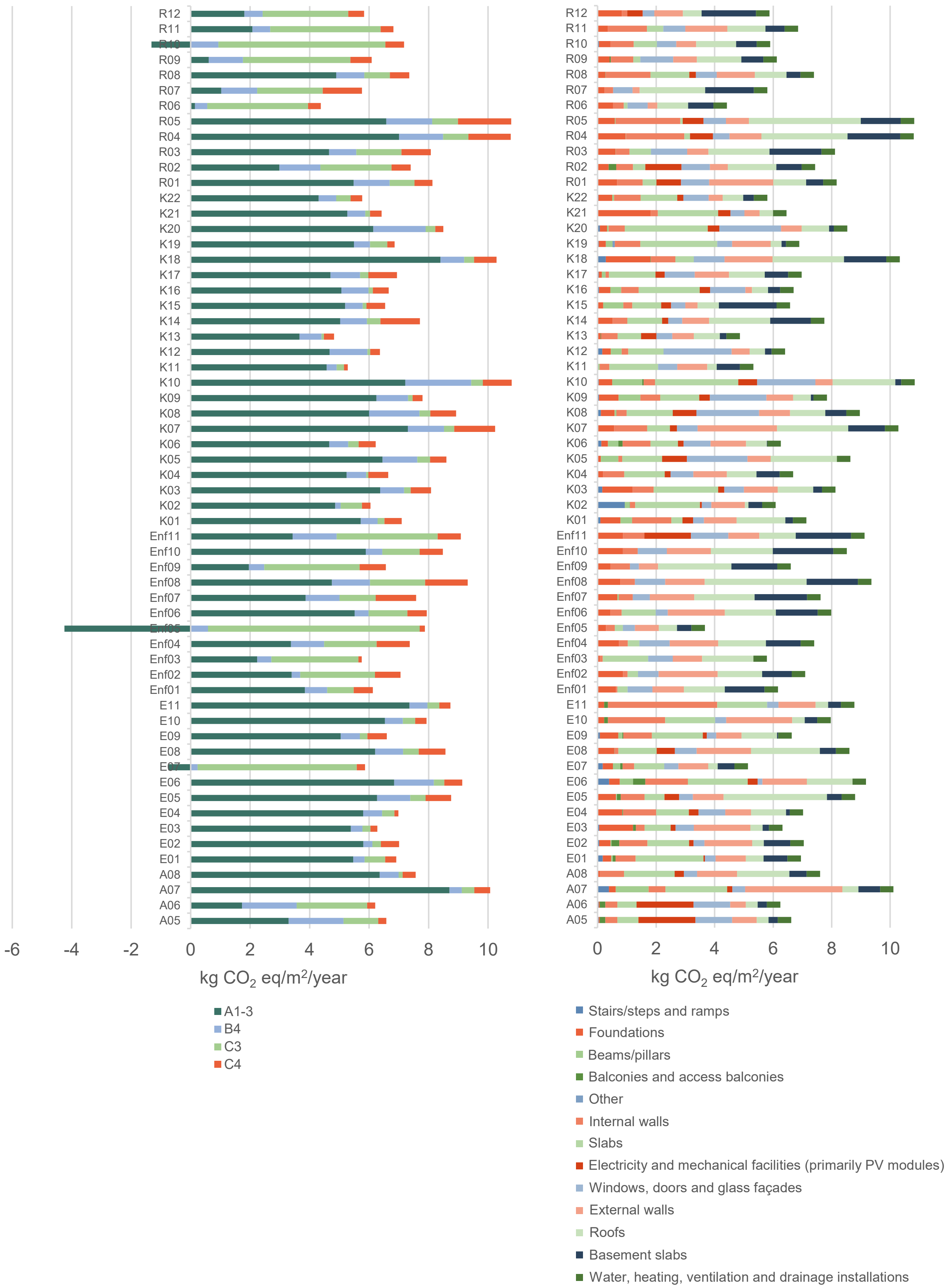



**FIGURE 10.** GWP of materials from the 60 case buildings over a 50-year reference study period broken down by life cycle stage (left) and building part group (right), respectively. GWP for operations is not included in the graph.

Figure 11 shows impacts from operational energy in kg $CO_2$ eq/$m^2$. Again, the results are shown on a time axis as kg $CO_2$ eq/$m^2$, showing that operational energy is decreasing over time. This is because the energy composition used in LCAbyg has been projected according to national goals for a gradually larger renewable energy share in the future, and this will have a lower GWP. This transition to renewable energy production has the greatest effect on electricity production. This means that buildings with high electricity consumption, especially buildings with electric heat pumps, will have greater reductions in impacts over time compared with buildings with district heating as their heating source.

Figure 11 shows a significant spread in the results for operational energy use (from 11 to 230 kg $CO_2$ eq/$m^2$ at 50 years) (see figure 11). However, the figure also shows that this spread includes two cases with a significantly lower operational energy use than the remaining case buildings, as well as a case with a significantly higher operational energy use. The case buildings with a low operational energy use only have contributions from electricity consumption, as these are heated with a heat pump. This results in low environmental impacts from operations over time. However, the high contribution from operational energy use is due to one building having a relatively high heating demand from district heating.

In general, the spread in GWP of operational energy use is partly due to the composition of energy, as described earlier, but also due to the size of the energy demand. Here, differences in the energy frame and the possibility to obtain a supplement to the energy performance framework may influence the operational energy demand. Apart from the three extreme cases, impacts from operational energy use vary between 65 kg $CO_2$ eq/$m^2$ and 154 kg $CO_2$ eq/$m^2$ (over a 50-year reference study period) for the case buildings (see figure 11).

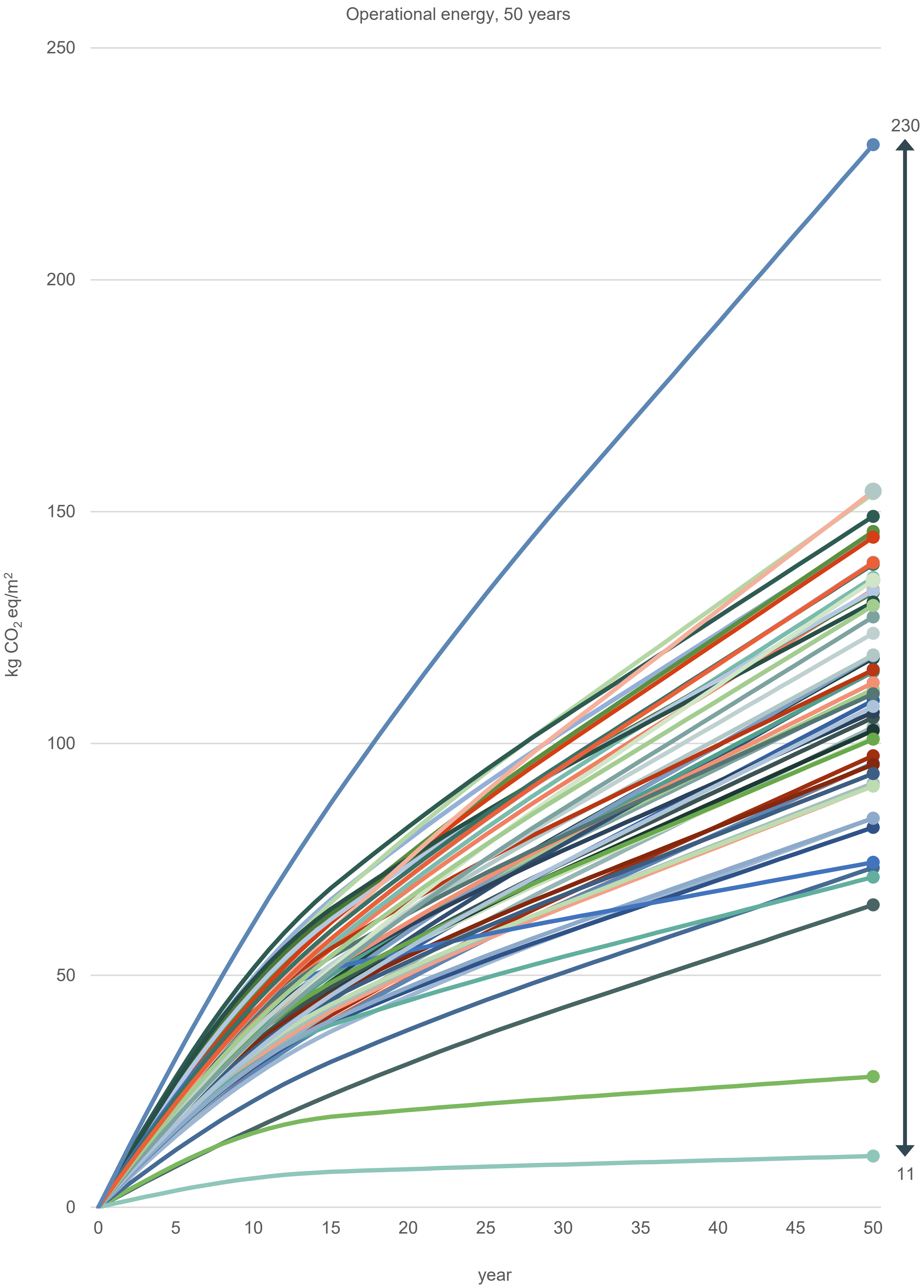



**FIGURE 11.** Accumulated GWP of operational energy use of the case buildings for a 50-year reference study period. GWP is stated per m² of heated gross floor area. GWP for materials is not included in the graph.

# 5 RESULTS FROM LCA IN AN 80-YEAR REFERENCE STUDY PERIOD

## 5.1 Results from LCA of case buildings

This section shows the results of all case buildings in an 80-year reference study period in kg $CO_2$ eq/m$^2$ or kg $CO_2$ eq/m$^2$/year. The results include all 60 case buildings, and adjustments have been made for missing data on technical installations, as described in section 3.2.

Figure 12 shows the impact from the case buildings calculated over an 80-year reference study period and shown per m$^2$/year. The figure shows large variations between total GWP of the case buildings, where some buildings have up to 2.5 times greater impacts from both materials and operations than other buildings (varying from 4.92 to 12.39 kg $CO_2$ eq/m$^2$/year). Moreover, the figure shows that impacts from the building materials are typically 2-4 times greater than impacts from operational energy use. Impacts from materials vary from 3.11 to 9.50 kg $CO_2$ eq/m$^2$/year, whereas impacts from operational energy use vary from 0.17 to 4.30 kg $CO_2$ eq/m$^2$/year.

As is the case for the results of a 50-year reference study period, it is important to note that the actual impacts from operational energy use and from materials are likely to be higher than those calculated. Again, this is because the operational energy use is based on data from the energy performance framework calculation, and this is usually underestimated in relation to the actual consumption. Moreover, not all life cycle stages have been included in the calculation, and therefore the actual impact from materials will be higher.

It should be further noted that case building Enf11 has no impacts from operations, because it has no data for operational energy use.

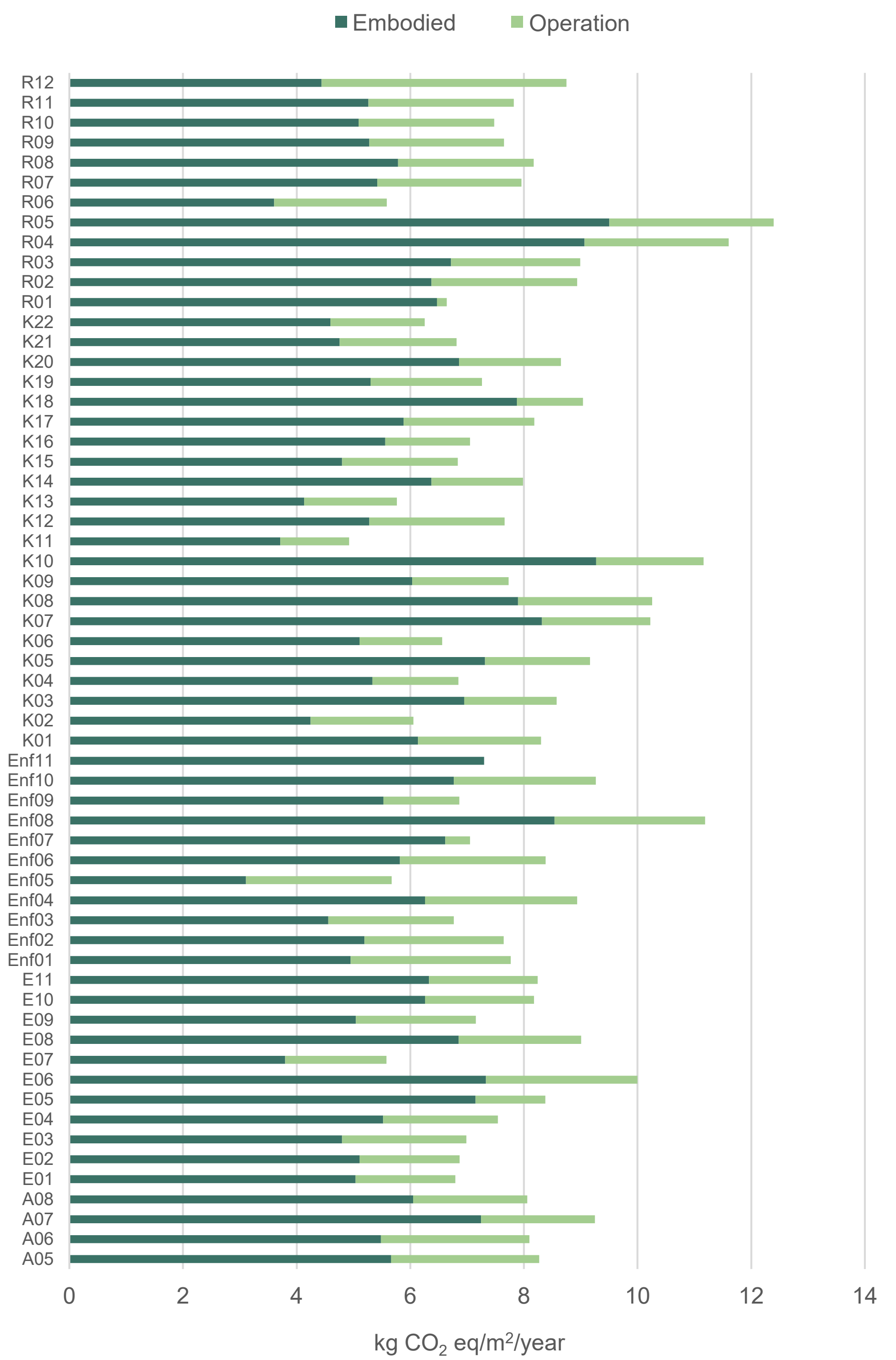



**FIGURE 12.** GWP of the 60 case buildings over an 80-year reference study period broken down by embodied carbon emissions (materials) and operational carbon emissions. Enf11 has no data for operations, and therefore only results for materials are shown.

Figure 13 illustrates how impacts from materials are distributed on an annual basis. The results are shown on a time axis in kg $CO_2$ eq/m$^2$, and it is clear that some impacts are upfront, whereas others are part of a future scenario. The figure shows that the GWP of materials for most buildings is highest in year 0 when the building is constructed. In line with the 50-year reference study period, some buildings have a low or negative impact in year 0, but a high impact in year 80 when the reference study period ends. This is because these buildings have a greater share of wood products which store biogenic carbon, resulting in a low impact in the product stage (see section 4.1 and 3.2 for a more detailed explanation).

Replacement of materials (stage B4) is stated as impacts between year 0 and year 80. Figure 13 shows that the impacts from replacements happen in years 15, 20, 25, 30, 40, 50 and 60, which usually corresponds to replacement of paint, roofing felt, double-glazed windows, photovoltaic modules, technical installations and surfaces (façade material, floors and ceilings).

The figure also shows that, at the end of the reference study period in year 80, the total GWP of materials for all case buildings varies from 250 to 760 kg $CO_2$ eq/m$^2$. This shows that there is a potential to reduce total impacts per m$^2$ via the selection of materials.

Figure 14 to the right shows that impacts from materials primarily come from the building part groups roofs, external walls and slabs/basement slabs. As is the case for the 50-year reference study period, some case buildings do not differentiate between slabs, basement slabs and roof slabs. This is because of different choices in the LCA, which is typical in DGNB-certified and external projects (see section 4.1).

Moreover, figure 14 shows large impacts from the groups Windows, Internal walls, Foundations and Photovoltaic modules (where these are included). Once again this emphasises that, regardless of reference study period, the large building part groups account for the highest share of total impacts for the case buildings, and that this is where the greatest potential exists to reduce environmental impacts from buildings.

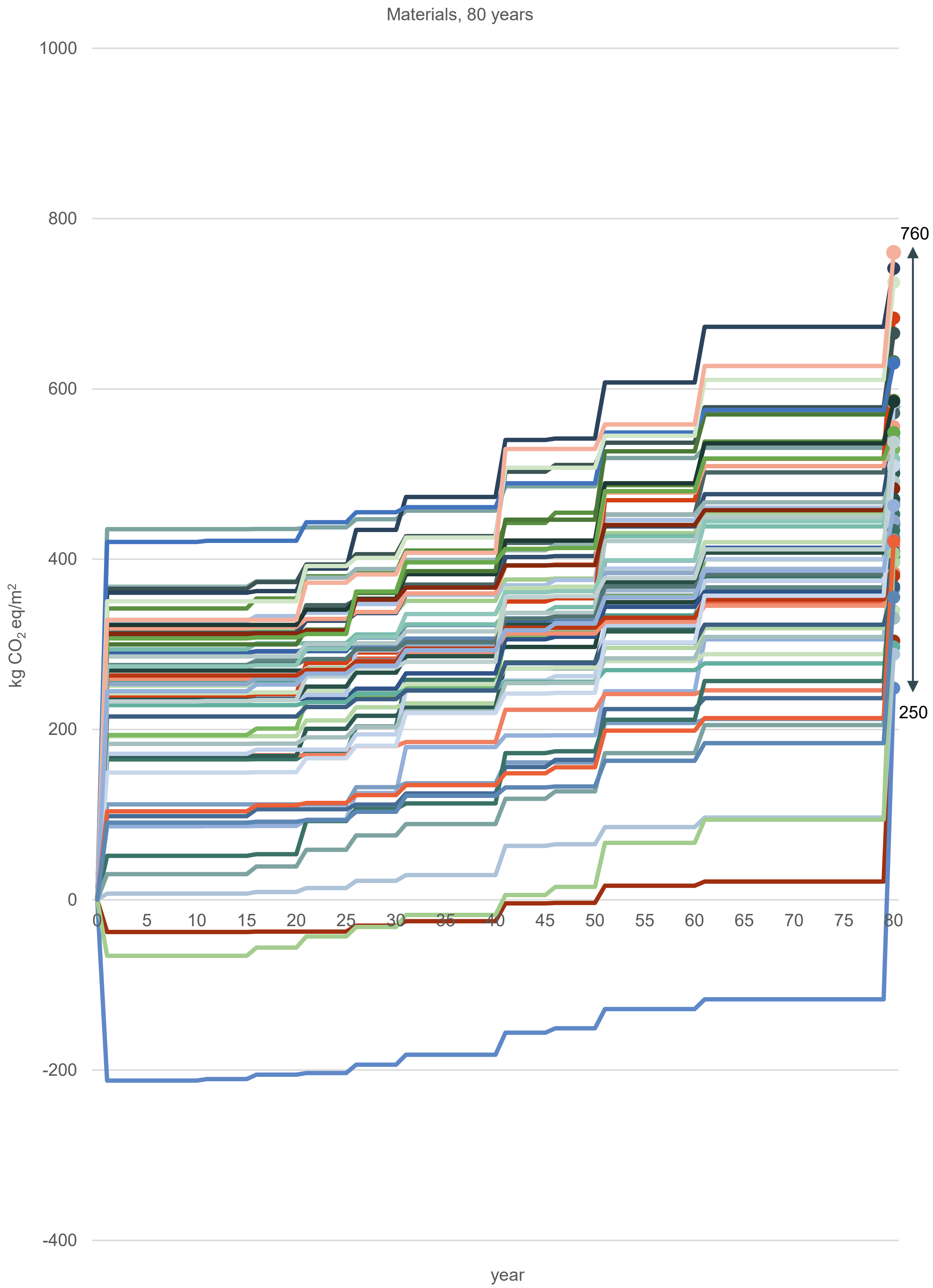



**FIGURE 13.** Accumulated GWP of materials of case buildings over an 80-year reference study period. GWP is stated per m[2] of gross floor area. GWP for operations is not included in the graph.

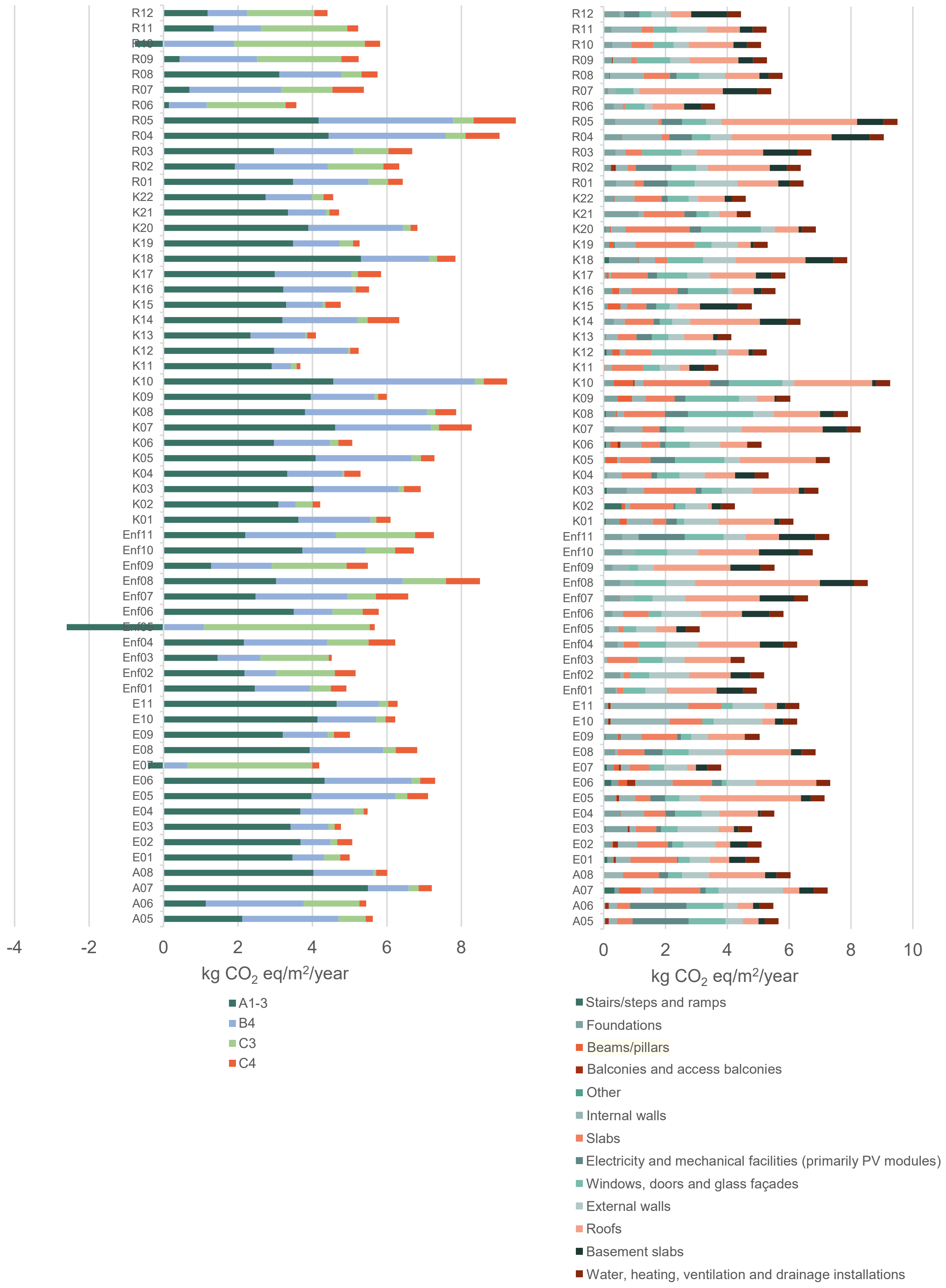



**FIGURE 14.** GWP of materials of the 60 case buildings over an 80-year reference study period broken down by life cycle stage (left) and building part group (right), respectively. GWP for operations is not included in the graph.

Figure 15 shows impacts from operational energy in kg $CO_2$ eq/m$^2$. Again, the results are shown on a time axis as kg $CO_2$ eq/m$^2$, showing that operational energy is decreasing over time. As is the case for the 50-year reference study period, this is because the energy composition used in LCAbyg has been projected according to national goals for a gradually larger renewable energy share in the future, and this will have a lower GWP (see section 4.1).

The figure shows a significant spread in the results for operational energy use (from 14 to 340 kg $CO_2$ eq/m$^2$ at 80 years). Again, the figure shows that the spread in operational energy use includes two cases with a significantly lower operational energy use due to heating with a heat pump, as well as a case with a significantly higher operational energy use due to a high heating demand from district heating (see section 4.1).

As is the case for the results of a 50-year reference study period, the spread in GWP of operational energy use is partly due to the composition of energy, but also due to the size of the energy demand. Apart from the three extreme cases, impacts from operational energy use vary between 93 and 231 kg $CO_2$ eq/m$^2$ (at 80 years) (see figure 15).

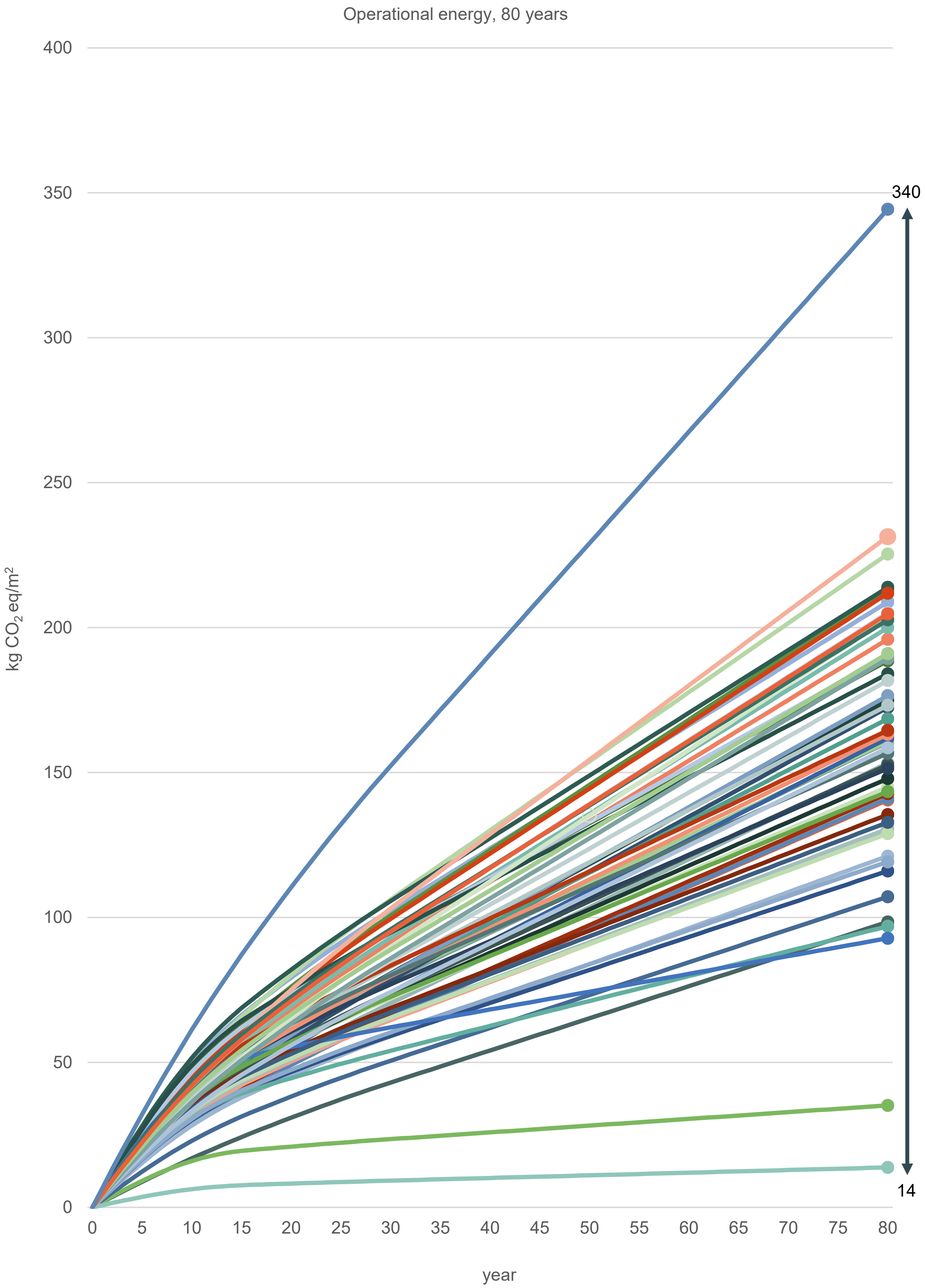



**FIGURE 15.** Accumulated GWP of operational energy use of case buildings over an 80-year reference study period. GWP is stated per m$^2$ of heated gross floor area. GWP for materials is not included in the graph.

# 6 PROMINENT CONDITIONS FOR WHOLE LIFE CARBON EMISSIONS AND BENCHMARK VALUES

This section analyses the LCA results of the 60 case buildings in terms of selected parameters considered relevant for the LCA of a building. The purpose is to examine the effect of these parameters on the whole life carbon emissions (Global Warming Potential, GWP) of buildings, as well as their potential influence on the development of benchmark values with the given combination of case buildings.

## 6.1 Reference study period

As described in section 3.2, the reference study period has an influence on the number of replacements of construction products and the length of the period during which operational energy is used in the building. Furthermore, the reference study period also affects the normalised result (kg $CO_2$ eq/m$^2$/year), as total impacts are broken down over the number of years in the reference study period. This means that, even though the total impacts for a long reference study period are greater than the impacts for a short reference study period, the impacts per year may be lower for a long reference study period, due to a larger number of years over which to distribute the impacts from materials used in the construction of the building. This is illustrated in figure 16, which shows the impacts of individual life cycle stages for all 60 case buildings over a 50-year and an 80-year reference study period.

Figure 16 shows that the impacts from the product stage (A1-3) and the waste processing and disposal stages (C3-4) are lower for a longer reference study period. For a 50-year reference study period, impacts from the product stage (A1-3) account for around half of the total impacts, whereas the same impacts for an 80-year reference study period account for just over one-third of the total impacts. Impacts from operational energy use (B6) are also lower for the 80-year reference study period. This is due to the projection for more renewable energy in the future. However, the figure also shows that impacts from replacement of materials (B4) increased with a longer reference study period, because, over time, more materials need to be replaced or because the materials need to be replaced several times. Impacts from replacements account for around 7% of total impacts for a 50-year reference study period, whereas replacements account for approximately 20% of total impacts with an 80-year reference study period. Since we are not sure about the number of replacements and the impacts from producing new materials when making replacements in the future, replacements can only be regarded as scenarios for the future, and a stronger focus on replacements consequently involves several uncertainties.

Note also that the cases with the lowest and highest GWPs are the same, irrespective of whether the reference study period is 50 years or 80 years (see figure 16). This means that the reference study period does not substantially change the ranking of the cases. The study by Rasmussen et al. (2020) lends further support to this.

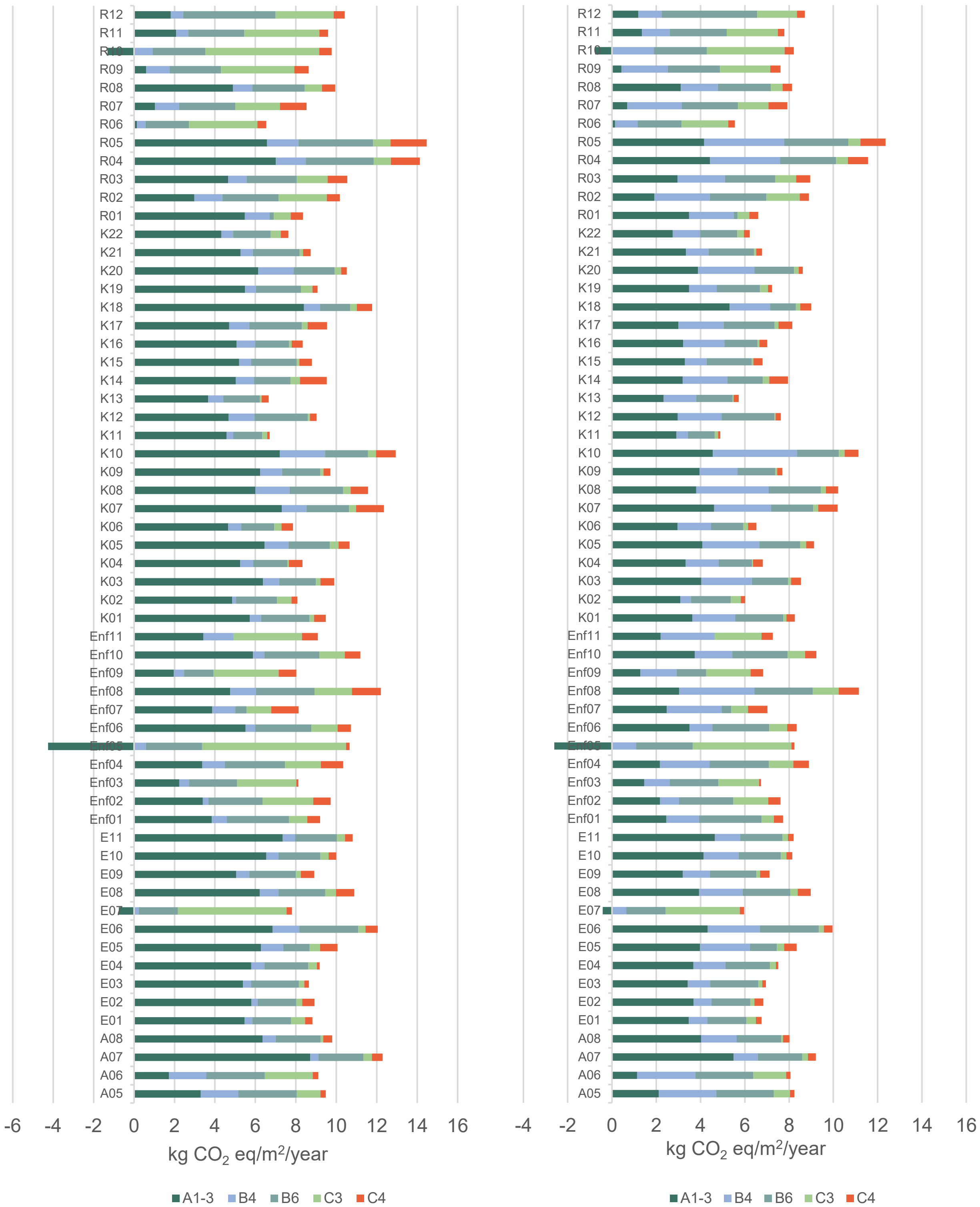



**FIGURE 16.** Buildings 50 (left) and 80 years (right). Replacements (B4) has a greater impact on the result with a reference study period of 80 years.

Figure 16 shows that some cases are relatively better with an 80-year reference study period compared with a 50-year reference study period. This applies in particular to cases K02, K11 and A07 where the upfront carbon emissions (A1-3) are relatively high compared with the other life cycle stages. With an 80-year reference study period, these cases have an advantage compared with a 50-year reference study period, because the upfront carbon emissions can be distributed over a larger number of years, thus reducing their significance. Conversely, case buildings with low upfront carbon emissions are relatively worse with an 80-

year reference study period compared with a 50-year reference study period. For example, this applies to cases R07 and R09, where upfront carbon emissions are not reduced to the same extent with an 80-year reference study period compared with a 50-year reference study period because the upfront carbon emissions are already low. Consequently, these buildings do not benefit considerably from spreading upfront carbon emissions over several years.

Furthermore, some cases do not necessarily have low upfront carbon emissions, but nevertheless are relatively worse with an 80-year reference study period compared with a 50-year reference study period. This applies in particular to Enf08, where the relatively worse impact with an 80-year reference study period is due to major replacements after 50 years, leading to considerably higher impacts. In this particular case, roof insulation has a relatively high GWP per $m^3$, and since the roof insulation is to be replaced after year 50, this leads to a significantly higher impact. Generally, the considerably higher impacts with an 80-year reference study period are caused by major replacements, particularly of roof insulation and façade materials.

Major impacts from replacements are usually caused by materials with a short service life that need to be replaced several times during the reference study period. This applies in particular for roofing felt, which turns out to have a major effect on the overall GWP in connection with long reference study periods because it is replaced every 20 years, see the service life table in SBi-2013:30 (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013). See table 4 for a list of construction products replaced in different reference study periods. An even longer reference study period, for example 120 years, will lead to increased impacts from replacements of load-bearing structures, for example.

**TABLE 4.** Replacements of construction products with 50-year, 80-year and 120-year reference study periods, see SBi-2013:30 (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013).

| | Replacement of construction product | | |
|---|---|---|---|
| | **50-year reference study period** | **80-year reference study period**[a] | **120-year reference study period**[b] |
| *Basement slabs and foundations* | None | Insulation | Basement slab |
| *Roof* | Roofing felt, plastic and wooden surfaces<br>Insulation made from plastic and<br>bio-based materials | Concrete, brick and metal surfaces<br>Mineral wool insulation | Natural stone surfaces |
| *External walls* | Double-glazed windows<br>Painted surfaces | Window frames<br>Metal and wooden surfaces<br>Insulation made from plastic and bio-based materials | Load-bearing aerated-concrete structures<br>Concrete and brick surfaces<br>Mineral wool insulation |
| *Floor slabs* | Linoleum floor coverings<br>Suspended ceilings | Built-on ceilings | Load-bearing wooden and LECA concrete structures<br>Wooden, concrete and brick floor coverings<br>Concrete and wooden ceiling surfaces |
| *Internal walls* | Wooden surfaces | Plaster and metal surfaces | Concrete, metal and wooden structures<br><br>Concrete and brick surfaces |
| *Technical installations* | Supply installation – plumbing<br>User installations | Distribution installations | Electricity supply |

[a] construction products replaced in a 50-year reference study period will often be replaced again once or several times with an 80-year reference study period (depending on the construction product service life)
[b] construction products replaced in a 50-year or an 80-year reference study period will often be replaced again once or several times with a 120-year reference study period (depending on the construction product service life)

The sections below examine how other prominent parameters may influence the results of LCAs of buildings and consequently affect the benchmark values. As the GWP with long reference study periods is based more on future scenarios and therefore involves several uncertainties, and as the upcoming European Level(s) framework indicates a 50-year reference study period (see section 3.2), the analyses below are based on a 50-year reference study period.

## 6.2 Building type and design

The GWP of different types of building is examined using homes and offices as examples and based on a 50-year reference study period, and this is in line with the future version of Level(s). The aim is to analyse possible links between building type and GWP that may cause differences in the GWP of buildings and consequently lead to differentiated benchmark values. Moreover, building designs are examined on the basis of building types. Figure 17 shows impacts from the building cases, broken down by building type. The figure shows results for the three types of home, offices and other buildings in kg $CO_2$ eq/$m^2$/year over the 50 years for which impacts from buildings are calculated. The figure shows that there is no big difference in impacts for different building types, neither in terms of impacts from operational energy nor impacts from materials.

Impacts from operational energy are slightly lower for office buildings and apartment buildings because the heating consumption in these buildings, not least in office buildings, is lower. Furthermore, apartment buildings with photovoltaic modules have lower electricity requirements.

Impacts from materials for all building types vary considerably, with a spread ranging from 3.7 to 10.8 kg $CO_2$ eq/$m^2$/year. However, looking at the average value and the median values, the results for the different building types are not that different: The figure shows that for homes, the median values for the GWP of materials are 7.4, 7.1 and 7.0 kg $CO_2$ eq/$m^2$/year for detached houses, terraced houses and apartment buildings, respectively. The median value is highest for detached houses, but it is only 7% higher than the median value for offices, which have the lowest value at 6.9 kg $CO_2$ eq/$m^2$/year. Looking instead at the average value, detached houses have the lowest value, while apartment buildings have the highest value. The data basis for other buildings only consists of four case buildings, and thus constitutes a very small basis on which to draw conclusions. Overall, the results do not give rise to a clear differentiation on the basis of building type.

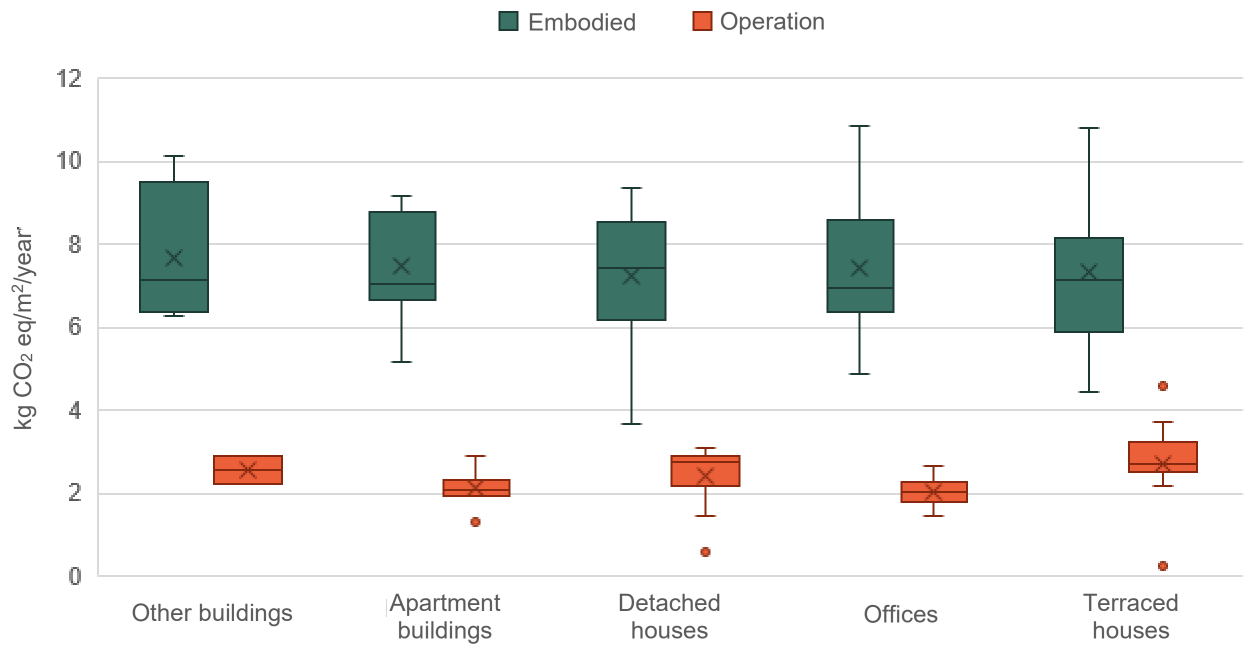



**FIGURE 17.** GWP of building parts and operation with a 50-year reference study period. There is no major difference between the building types. The chart shows the first, second and third quartile as horizontal lines in the box, the cross in the box shows the average value and the tails outside the box show the variance. The dots are observations for GWP outside the variance. Results for other buildings should be interpreted with caution, as they only include four cases.

Figure 18 shows the distribution of impacts from case buildings as the accumulated impact over 50 years for each building type. This means that the figure shows the immediate impact in year 0 when the building is built, and the gradual increase as materials are replaced over the 50 years for which the impact of the building is calculated. The figure shows that there is a major difference in GWP within each of the building types. The lowest GWP per square metre of a building is calculated at 180 kg $CO_2$ eq/$m^2$/year for a detached house, and the highest impact is calculated at 540 kg $CO_2$ eq/$m^2$/year for both terraced houses and office buildings. When excluding other buildings, for which we have very few cases, the total GWP varies by a factor of 1.8 for apartment buildings to 2.6 for detached houses.

Detached houses and terraced houses have a larger share of embodied carbon impacts from waste processing in stage C, which is the last increase on the curve over 50 years, see also figure 9 in section 4. The main reason is that both building types include a larger share of cases with wood products (see table 1 or Annex I, table 8). As described in section 3.2, wood products store biogenic carbon ($CO_2$), which is then released during waste processing. This release during waste processing is included in the LCA, irrespective of whether the wood is assumed to be incinerated, reused or recycled at the end-of-life stage. Consequently, it is important to take into account that buildings with a large share of biogenic material will have a low GWP during the product stage (modules A1-A3) and a higher GWP at the end-of-life stage (modules C3-C4).

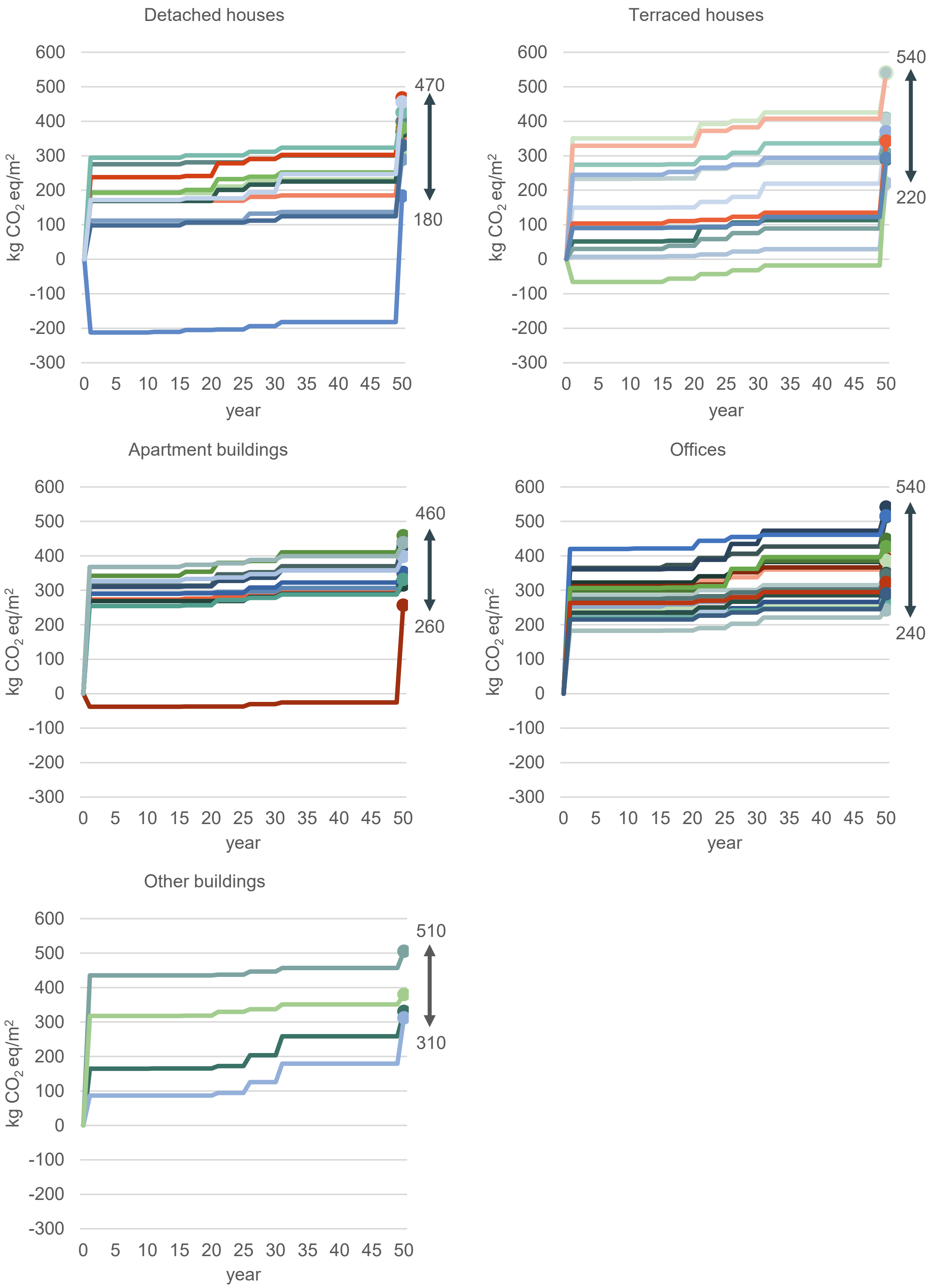



**FIGURE 18.** GWP of materials accumulated over 50 years. Each line/colour represents one case. The accumulated graphs show a greater spread in terms of when the impacts occur for the individual case buildings.

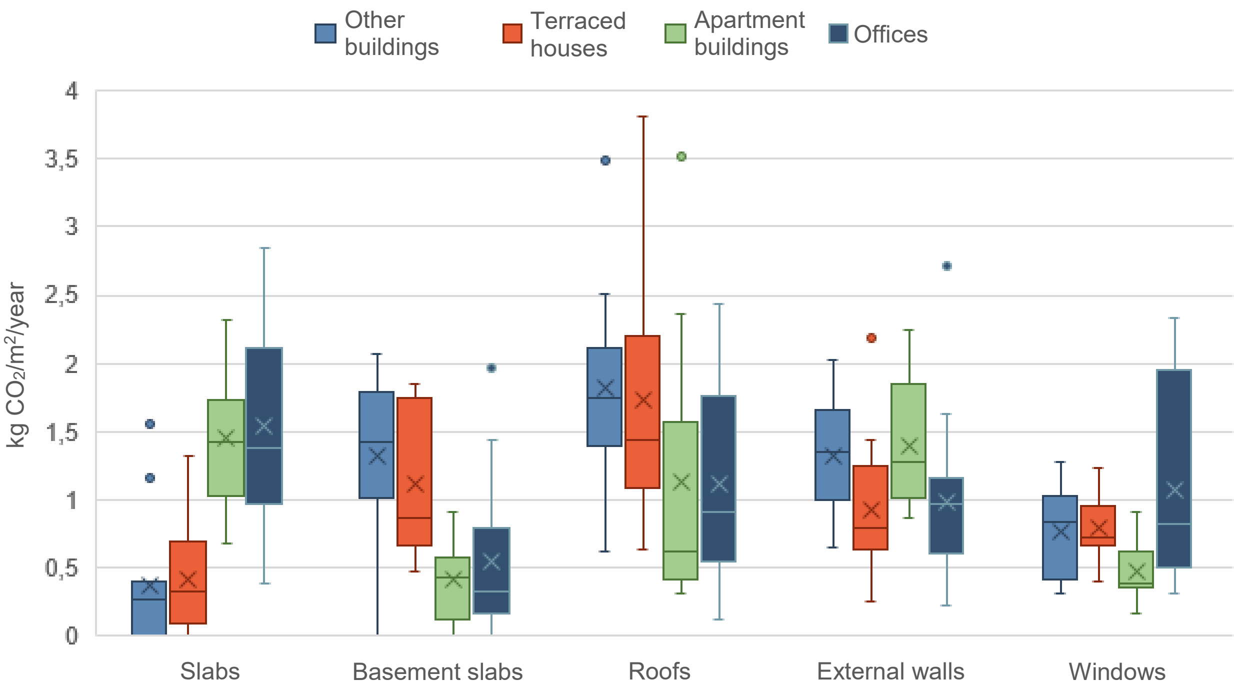



**FIGURE 19.** Impacts from selected building part groups broken down by building types, for a 50-year reference study period. The building type 'Other buildings' has not been included because the number of cases in this category is insufficient. The chart shows the first, second and third quartile as horizontal lines in the box, the cross in the box shows the average value and the tails outside the box show the variance. The dots are observations for GWP outside the variance.

Figure 19 shows GWP of selected building part groups broken down by building types. The figure reflects the design of building types, for example in relation to height, compactness and type of façade.

The apartment buildings and offices examined all exceed 1,000 $m^2$ and have more floors than detached houses and terraced houses. The gross floor areas of detached houses and terraced houses are significantly smaller and the houses only have 1-2 floors. This difference manifests itself in a characteristic distribution of impacts from basement slabs, slabs and roofs. As they are multi-storey building types, offices and apartment buildings have high impacts from slabs, but lower impacts from basement slabs and roofs. However, the difference is less significant for roofs than for basement slabs. This is because flat roofs are more common on tall buildings, and flat roofs involve the use of pressure insulation and roofing felt, both of which have a high GWP.

In the categories of external walls and windows, detached houses have the largest impacts. This may be due partly to the area of the building envelope relative to the total gross floor area. As in other building part groups, there is a considerable spread in results, especially for windows in office buildings. This is because some, but not all, case buildings have glass façades, which result in high impacts.

Overall, there is a shift in impacts within the building part groups. Considering all case buildings together, the results balance out, which means that there is no significant difference between the building types. However, this will not necessarily apply for the individual projects, and consequently, building design is still important in relation to GWP. The exact correlations have not been examined in this project, but it would be relevant to look into these in the future.

The composition of materials is also important, as we have seen in connection with roof structures, glass façades and wooden structures. The building types have been selected to reflect the variation in materials in ordinary buildings, but they do not constitute a statistically

representative sample of the composition of materials for Danish building types. The composition of materials in the case buildings is described in table 1.
The building types do not show substantially different impacts. Consequently, different benchmark values will not be stated for the different building types.

## 6.3 Photovoltaics

This section examines the influence of photovoltaic modules on the GWP of case buildings, and how photovoltaic modules may affect the benchmark value. The analysis is based on a 50-year reference study period in accordance with the draft version of Level(s).

In 37 of the 60 case buildings, photovoltaic modules have been installed to produce electricity in the building. However, there is some variation with regard to the percentage of photovoltaic modules in the buildings. When we look at the photovoltaic area relative to the gross floor area, we can see that the photovoltaic area makes up between 1% and 22% of the gross floor area.

Photovoltaics are responsible for a large part of the impacts from building parts. Figure 20 shows the relationship between the photovoltaic area relative to the gross floor area and the percentage of impacts from photovoltaic modules relative to the total impacts from building parts. This relationship can best be described as linear, as illustrated by the figure. This means that if we add a photovoltaic area corresponding to 10% of the gross floor area, we can expect the photovoltaic modules to account for approximately 12% of the building's total GWP from building parts.

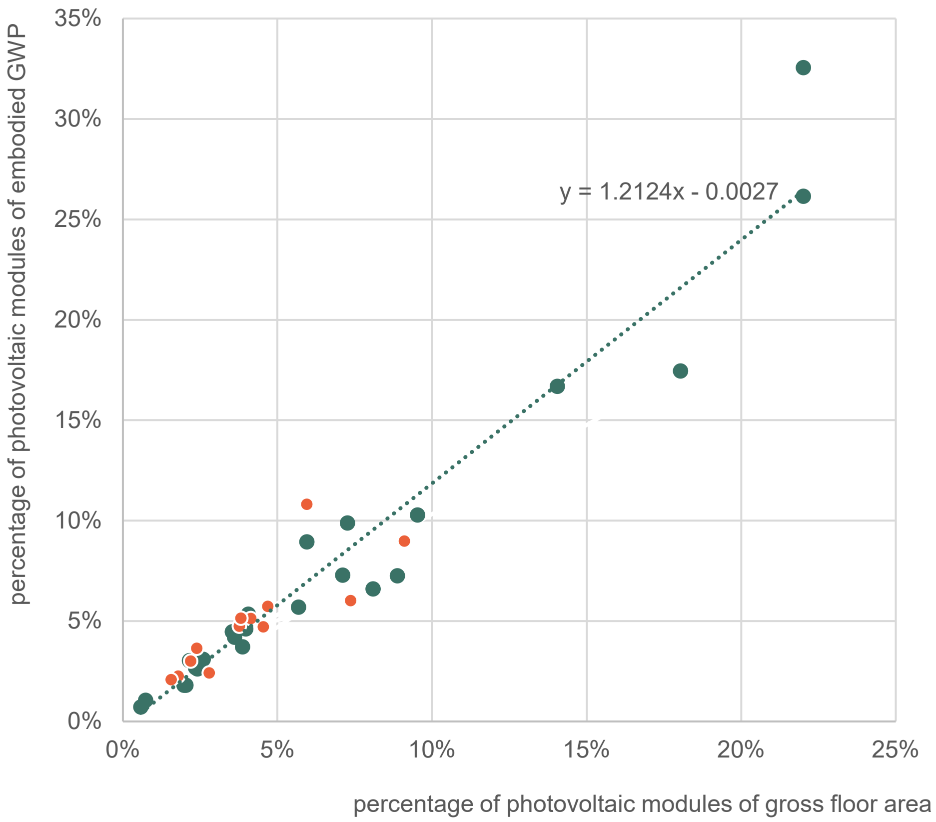



**FIGURE 20.** The area of photovoltaic modules relative to the percentage of photovoltaic modules of embodied GWP over a 50-year reference study period. Impacts from photovoltaic modules may be of great significance for the total environmental impacts of the building. The cases marked in orange correspond to the case buildings in figure 21.

Implementing photovoltaic modules in a building reduces the energy demand from the energy grid. When the building has local production of electricity, such local production is deducted from the building's energy demand in the LCA, and this will result in a lower or a negative GWP from electricity consumption for operation. However, the production of photovoltaic modules is added to the material consumption of the building, which makes the GWP of the building increase. The higher impacts from materials and the reduction in impacts from operations are illustrated in figure 21 for the selected case buildings, calculated over a period of 50 years. Overall, this results in the change in the building's total impacts from implementing photovoltaic modules shown on the right side of the figure. The figure shows that total impacts from the building increase slightly when implementing photovoltaic modules, because the impact from materials outweighs the impact of savings during operations.

One of the reasons that photovoltaic modules have not had a significant effect on the GWP is that the electricity from the electricity grid substituted by the photovoltaic modules already contains a large share of renewable energy. Moreover, the share of renewable energy in the electricity grid will increase up to 2050, and this is also included in the LCA. Another reason is that the expected service life of photovoltaic modules is 30 years, which means that a replacement will take place during the reference study period.

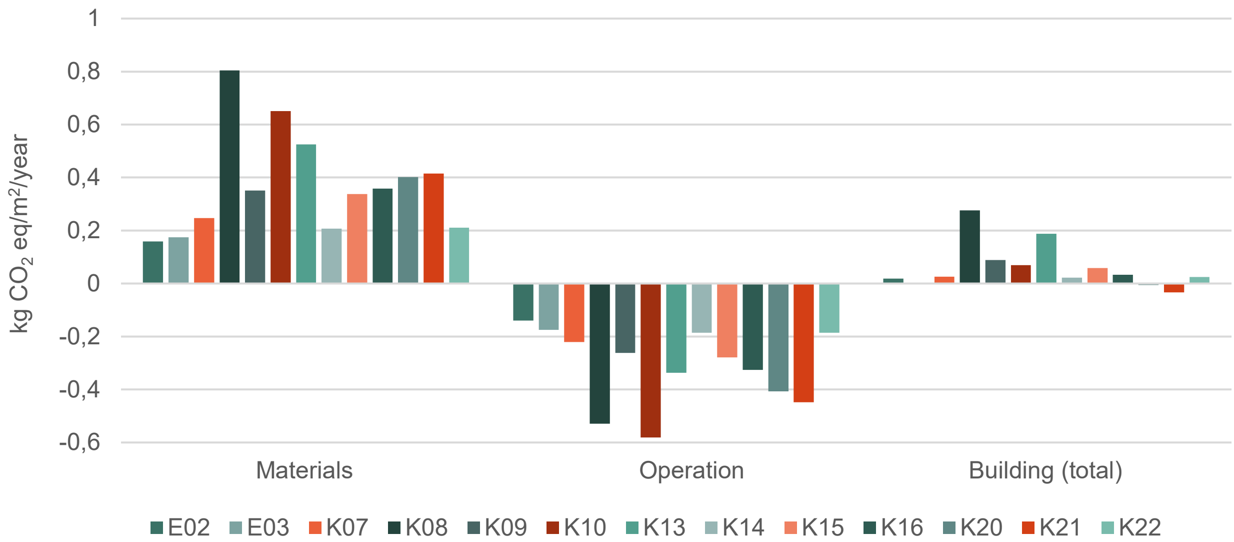



**FIGURE 21.** Change in GWP when photovoltaic modules are implemented in the case buildings.

However, there is a possibility that photovoltaic modules will be advantageous in the first years up to 2050. Figure 22 shows that the photovoltaic modules installed when constructing the building (year 0) will pay back over a period of 8-19 years in terms of GWP. However, installation of new photovoltaic modules when replacing the modules after 30 years may not pay back within the period (figure 22) . Replacement of the photovoltaic modules may not necessarily pay back because of the large share of renewable energy in the electricity supply expected in 30 years' time, and because the GWP of replacing the photovoltaic modules in year 30 is based on the same dataset as for year 0 (something which also applies to all other components and materials to be replaced). However, it is not possible to predict how photovoltaic modules will be manufactured in 30 years' time, nor is it possible to include such projections in building LCAs today, so this has been assumed.

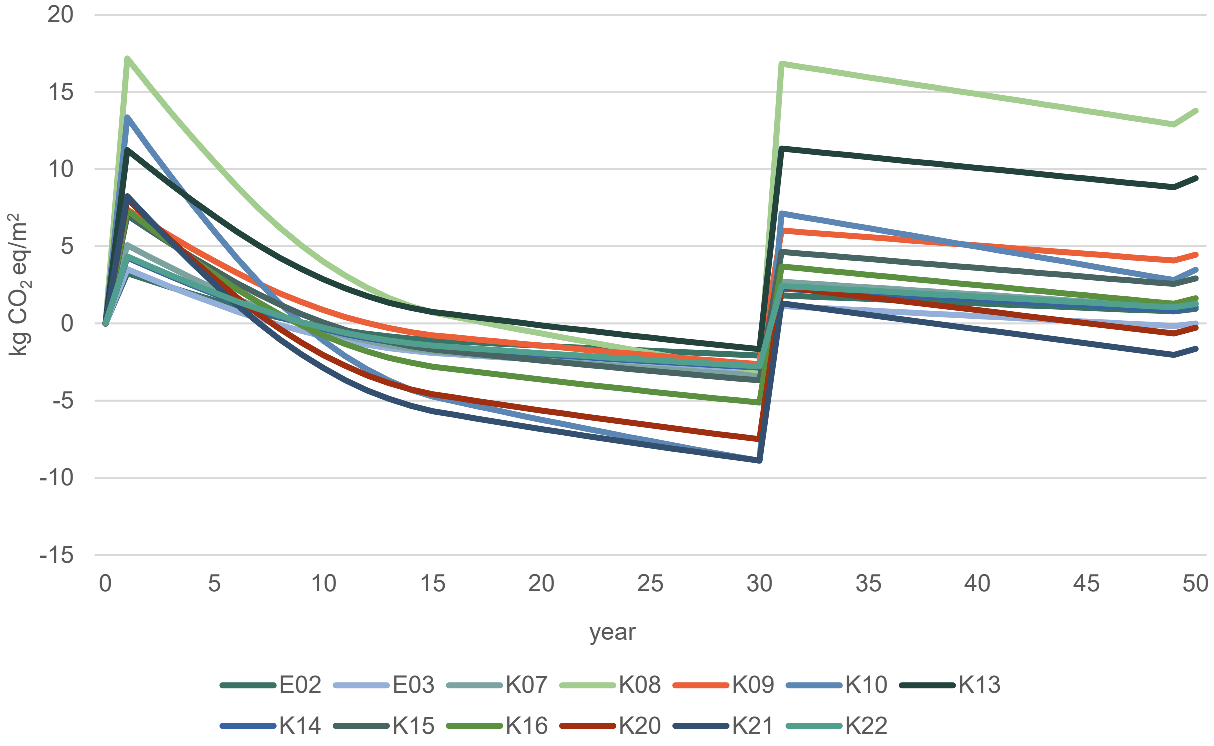



**FIGURE 22.** Impact of photovoltaic modules on case buildings over time. The figure shows the accumulated sum of impacts from materials and reduced impacts from operations of photovoltaic electricity production. Electricity production from photovoltaic modules has the greatest effect on GWP over the first approximately 10 years. After this, the share of renewable energy in the electricity mix is likely to have increased. The photovoltaic modules in the building will be replaced after 30 years, which means that in most cases, the GWP of photovoltaic modules is eventually positive.

When considering photovoltaic modules in the context of the total GWP of buildings, the change in GWP for the building as a whole is below 1% in most cases, and occasionally up to 3%. Consequently, whether photovoltaic modules are included in the calculation has no great significance for the overall influence of the building on GWP, when calculating over a period of 50 years. Figure 22 indicates that photovoltaic modules have a positive impact on the green transition for the next decade, but that it is uncertain whether this will still apply after 2030. This depends on how photovoltaic modules are manufactured in the future, and on developments in the GWP of energy supply. The calculations also indicate that it should be considered whether to exclude replacement of photovoltaic modules after 30 years from the LCA calculations for buildings, although this would be a departure from European standards. In the long term, hopefully the possibility to make projections for production of building materials can be incorporated into the building LCA.

Consequently, when calculating benchmark values, it does not play a major role whether photovoltaic modules are included, as long as the benchmark value encompasses all life cycle stages. However, if the benchmark value is broken down by building part (modules A1-3, B4, C3, C4) and operation (module B6), case buildings with photovoltaic modules will contribute to an increased impact for building parts and reduced impacts for operation.

## 6.4 Energy class

The case buildings were constructed in accordance with the requirements for energy classes 2010, 2015 and 2020. This section examines the influence of energy class on the GWP of a building as well as the effect on the benchmark value. The GWP of the case buildings is analysed in terms of different energy classes, and related to a single example in which two similar buildings, one in energy class 2015 and one in energy class 2020, are compared. The analyses are based on a 50-year reference study period, which is in line with the future version of Level(s).

Table 5 shows the number of case buildings in energy classes 2010, 2015 and 2020 included in the analysis. The energy class for 2015, which may be Low-energy Class 2015 in the Danish Building Regulation 2010 (BR10) and a minimum requirement in BR15 and the current BR18, accounts for the largest share. The table also shows that low-energy buildings, i.e. Building Class 2020, see BR10/15 and low-energy class, see BR18, constitute a larger share of the cases than the actual share of low-energy buildings built today. In 2018, this was 10-12% (AAU BUILD and the Danish Energy Agency, 2019).

**TABLE 5.** List of energy classes for case buildings included in the analysis.

| | **Number of cases** |
|---|---|
| **Energy class 2010** | 2 |
| **Energy class 2015** | 39 |
| **Energy class 2020** | 19 |

Figure 23 shows that there are minor differences in the embodied carbon impacts for case buildings with energy class 2010, 2015 and 2020. On average, the embodied carbon impacts constitute 7.79 kg $CO_2$ eq/m$^2$/year for class 2010, 7.24 kg $CO_2$ eq/m$^2$/year for class 2015 and 7.66 kg $CO_2$ eq/m$^2$/year for class 2020 buildings. However, it is difficult to identify a pattern of impacts from buildings constructed in accordance with energy class 2010, because only two energy class 2010 buildings are included in the analysis. When buildings in energy classes 2015 and 2020 are considered alone, the embodied carbon impacts increase by around 5% from 2015 to 2020 depending on energy class.

As illustrated in figure 23, impacts from operational energy use decline steadily from energy class 2010 to 2015 and 2020. Again, looking only at energy classes 2015 and 2020, the impact from operational energy use falls by 8%. The increasing impact from materials and the declining impact from operational use can be attributed to the Building Regulations requirements for reduced energy demand. This usually leads to an increase in the quantity of insulation in the foundation, basement slab, external walls and roof combined with lower operational energy use, resulting in a shift in impacts to higher embodied carbon impacts and lower impacts from operational use. However, this is not considered a significant shift of impacts.

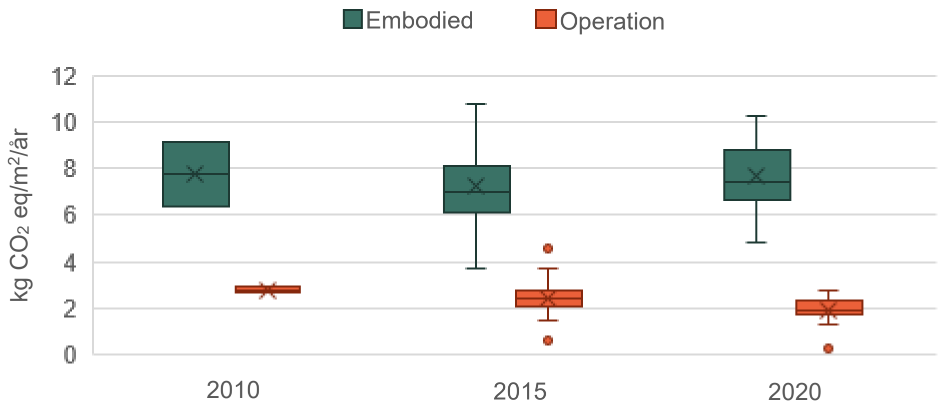



**FIGURE 23.** Distribution of impacts from materials and operation for energy class 2010, 2015 and 2020 with a 50-year reference study period. The chart shows the first, second and third quartiles as horizontal lines in the box, the cross in the box shows the average value and the tails outside the box show the variance. The dots are observations for GWP outside the variance.

The analysis above includes a large number of cases with different characteristics, such as consumption of more or less harmful materials, higher quantities of insulation and lower operational energy use than necessary under the energy class. These different characteristics may influence the results and make it difficult to analyse the effect of energy class on the overall environmental impact. Consequently, two specific cases have been analysed to exemplify the implications of requirements for lower energy use for the environmental impact from materials and operation. The analysis below is based on a building constructed in accordance with Building Regulations 2015 (BR15) and energy class 2015, and on a building constructed in accordance with Building Regulations 2018 (BR18) and energy class 2020. In order to clarify the importance of energy classes, the buildings had to be as similar as possible, and consequently, the two buildings are from the same engineer/contractor and have the same overall design. The different parameters that we considered to be relevant for the comparison are listed in table 6.

**TABLE 6.** List of parameters for the two buildings

| | 2015 case building | 2020 case building |
|---|---|---|
| **Energy class** | 2015 | 2020 |
| **Building Regulations** | 2015 | 2018 |
| **Operational use, heating** | 39.8 kWh/m$^2$/year | 18.6 kWh/m$^2$/year |
| **Operational use, electricity** | 1.8 kWh/m$^2$/year | 2.5 kWh/m$^2$/year |
| **Area** | 134 m$^2$ | 179 m$^2$ |
| **Load-bearing structures (external wall + roof)** | Wood | Wood |
| **Façade cladding** | Wood | Wood |
| **Roof surface** | Brick | Brick |
| **Windows** | Wood | Wood |
| **Thickness of insulation, external wall** | 240 mm | 240 mm |
| **Thickness of insulation, roof** | 495 mm | 550 mm |

Table 6 illustrates that the buildings are comparable with regard to the materials used. The overall structure of the building parts is also the same. The primary difference in 2020 compared with 2015 is thicker insulation in the roof. This of course leads to a higher consumption of insulation material as well as an extension of the timber structure to make room for the additional insulation. Furthermore, operational use in the 2020 building has been reduced compared with the 2015 building. Finally, the buildings have different sizes, but as the results have been normalised to the gross floor area, the size difference is not likely to have a significant influence on the results.

Figure 24 shows that the greatest difference in impact between the 2015 and the 2020 building relates to the operation of the building. In the 2020 building, the impact from operational use was reduced by 1.5 kg $CO_2$ eq/m$^2$/year relative to the impact from operational use for the 2015 building. However, the embodied carbon impacts from building materials only increased marginally (around 4%) from the 2015 building to the 2020 building (from 6.46 to 6.75 kg $CO_2$ eq/m$^2$/year).

This analysis shows that the difference between a 2015 building and a 2020 building can be more significant when considering individual buildings, not least with regard to operational energy use. However, when all 60 case buildings are considered together, the results do not show any considerable difference (see figure 24). Based on this, it can be concluded that energy class may influence the results, but that the impact is likely to depend on other parameters, such as selection of materials and structural design, just as much as on energy class. Consequently, the fact that most of the buildings were in energy class 2015 is not assessed to have any major significance for the benchmark value.

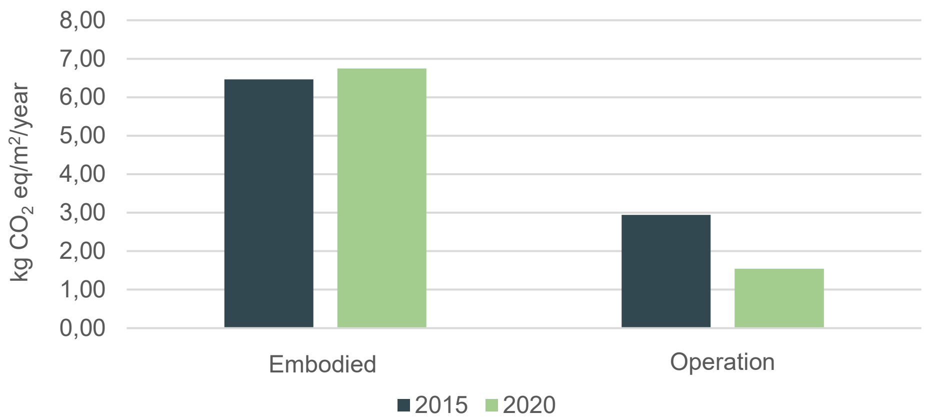



**FIGURE 24.** Distribution of impacts from materials and operation for an example house with BR15 and energy class 2015 and BR20 and energy class 2020 over a 50-year reference study period.

## 6.5 Secondary buildings

This section describes how secondary buildings (such as garages, sheds, etc.) affect the GWP of buildings. A reference study period of 50 years is used, which is in line with the future version of the European Level(s) framework. Of the 60 case buildings, only one includes secondary buildings. This means that the case buildings only reflect secondary buildings to a minor degree. This section examines the impact of a case building in order to illustrate the method when including secondary buildings in the LCA and to provide an example of the extent to which secondary buildings may influence the benchmark value.

The case building examined is a detached house modelled with and without a garage. The detached house has a heated gross floor area of 164 m$^2$ and an area of 214 m$^2$ with the garage. The garage is unheated and less than 50 m$^2$, and therefore, it is not included in the gross floor area (section 455 of the Building Regulations). The building has load-bearing concrete structures, a brick façade and a tall wooden roof structure. The garage adjoins the main building, and consequently, the garage has the same structural design as the main building for the external walls and roof.

The results show that the garage contributes to an increase in total GWP for the entire building of around 1.3 kg $CO_2$ eq/m$^2$/year (from 10.2 to 11.4 kg $CO_2$ eq/m$^2$/year). The reason is that more building materials are used when a secondary building is added. When the impact is then normalised to kg $CO_2$ eq/m$^2$/year, the impact from the building materials is distributed over the gross floor area, which is the same for both scenarios (due to section 455 of the Building Regulations). Consequently, the consumption of more building materials is normalised over the same area when a secondary building is added, and this leads to a higher impact per m$^2$/year. In this example, the clear increase in impact per m$^2$/year is also due to the fact that the garage is almost as materials-intensive as the main building. This will clearly not be the case for all secondary buildings, and consequently, this may be considered a worst-case scenario. In an example such as this, where the impacts per m$^2$ from the garage are as high as the impacts from the main building, the garage may account for 12% of the total GWP of the building. With only one out of the 60 case buildings that includes a secondary building, the additional impact from secondary buildings will only be reflected in the benchmark values to a small degree.

## 6.6 Summary

This section has examined how different parameters affect the results of an LCA, and how the parameters influence the development of the benchmark values calculated on the basis of the 60 case buildings. The parameters examined were: reference study period, building type, photovoltaic modules, energy class and secondary buildings.

In section 6.1 examining how the reference study period influences the GWP and benchmark value, it was found that replacements of materials have greater influence when there is a long reference study period, and that materials with a long service life, such as load-bearing structures, have less impact with a long reference study period. However, a short reference study period highlights the upfront carbon emissions because replacements become less important. On the basis of this, it was decided to use a 50-year reference study period for analyses concerning building type, photovoltaic modules, energy class and secondary buildings. This is also in accordance with the European Level(s) framework.

The analyses presented in sections 6.2 to 6.5 found no clear indication of a generalisable effect of the conditions described on the GWP of buildings or building types. Consequently, the cases examined do not support a differentiation of benchmark values for building types.

As described in section 6.2, there is no significant difference in GWP for the different building types. This applies to the embodied carbon impact from materials as well as impacts from operational energy use. However, there was a clear difference in the distribution of impacts between building parts, reflecting the design of the building parts, including their height, compactness and type of façade. The calculations also show a large variation in the embodied carbon impact within each building type, as the relationship between the impacts varies by a factor of 1.8 to 2.6 per square of metre building, irrespective of building type.

The analyses concerning photovoltaic modules presented in section 6.3 showed a slight increase in GWP when adding photovoltaic modules to a building. The reason is that impacts from materials outweigh the savings achieved during the operation stage. Consequently, whether or not photovoltaic modules are included is not of great significance for the total GWP of the building. It does, however, make a difference whether impacts occur at the operation stage or the materials stage, and this should be taken into account when selecting the type of benchmark value to be used. The analyses also showed that, based on the knowledge and data currently available on production of photovoltaic modules as well as the electricity supply they replace, photovoltaic modules can make a positive contribution to the green transition in the next decade. After this, installation of photovoltaic modules will no longer have a positive effect according to the calculations, unless there is a significant reduction in the GWP of producing photovoltaic modules, or the green transition of electricity supply progresses more slowly than expected.

The difference between buildings constructed according to energy classes 2010, 2015 and 2020 was examined in section 6.4. Based on the analysis of the total number of buildings, we found that the median value for building materials increased by around 5% from energy class 2015 to 2020, while the median value for the GWP of operational energy use decreased by around 8%. Thus, considering all the building cases as a whole, we did not find any major difference in total GWP between energy classes 2015 and 2020. Consequently, this analysis did not give rise to developing different benchmark values for 2015 buildings and 2020 buildings, respectively. In the single case that we studied in more detail, we found that, with a 0.28 kg $CO_2$ eq/m$^2$/year investment in materials (embodied carbon impact), there is a reduction of 1.5 kg $CO_2$ eq/m$^2$/year in operation, which shows a reduction in the overall GWP in this single case.

Section 6.5 presents the effect of secondary buildings on the GWP and benchmark values. Secondary buildings are only included in the benchmark values for one case building. As the addition of a secondary building increases the quantity of materials, but not the reference area used to calculate the GWP, as a general rule, the existence of secondary buildings will usually increase the GWP.

# 7 POSSIBILITIES TO DEVELOP BENCHMARK VALUES

## 7.1 Possibilities to develop benchmark values

Sections 4 and 5 presented the GWP for 60 case buildings, based on a 50-year and an 80-year reference study period, respectively. Subsequently, section 6 examined the importance of different aspects for LCA results for buildings as well as for benchmark values. These analyses were carried out on the basis of a 50-year reference study period, as this is in line with the European Level(s) framework. However, this section presents benchmark values for both a 50-year and an 80-year reference study period to include the possibility of applying a longer reference study period.

LCAs for 60 case buildings is the largest number of LCAs of buildings collected in Denmark to this date. Furthermore, the cases have been compiled in the same calculation tool, LCAbyg, and are therefore based on the same environmental data and the same method of calculation. When collecting the case building, attempts were made to include a broad selection of cases with different qualities in terms of building types, energy classes, materials, photovoltaic area, etc. This takes into account the differences between buildings, so that the data basis for the benchmark values is as representative as possible. This provides a sufficient basis for preparing benchmark values for voluntary schemes. Section 6 examines how the differences in the buildings may affect the benchmark values. As the data basis increases and more LCAs of buildings become available, the benchmark values should be updated.

The purpose of developing benchmark values for the GWP is to establish an unambiguous reference for the environmental performance over the life cycle of a building. A common benchmark value can form the basis for tender requirements, public regulation or other types of benchmarking that already exist for energy demand, indoor climate or other areas, but are missing for the life-cycle-based environmental impact in Denmark. Work on preparing LCA can be facilitated by carrying out an estimated LCA. Annex III illustrates how LCAbyg functions for an estimated LCA can be used to give a conservative estimate of the environmental impacts of buildings.

Basically, there are two different approaches to developing benchmark values: Top-down or bottom-up. In the top-down approach, benchmark values are determined on the basis of a specific goal, e.g. the political goal of limiting the global temperature rise to 1.5 degrees (Ministry of Climate, Energy and Utilities, 2015) or the Danish government's target of a 70% reduction by 2030. In this approach, benchmark values would be determined in relation to what is required to achieve the goal. The bottom-up approach takes outset in existing building practices and bases the benchmark value on common solutions available today. Typically, an average or median value will be calculated, and based on this, goals for gradual reductions will be established. This report applies the latter method, which is based on the analysis of the GWP of 60 existing case buildings.

The results of the LCAs are included in a statistical analysis to determine the benchmark values on the basis of the 60 case buildings. Possible benchmark values are then expressed as the median, upper and lower quartile, each of which suggest varying levels of ambition. The buildings with the lowest impacts can also be used as benchmarks. The benchmark values are stated for both a 50-year and an 80-year reference study period.

Another methodological aspect related to developing benchmark values is that the values may apply to the entire life cycle of the building over the reference study period, or they may apply to individual stages or to groups of stages. With regard to the benchmark values broken down by stages, note that a building may include elements that shift impacts from one stage to another. An example of this is biogenic carbon, because bio-based materials shift impacts from the product stage (A1-3) to the waste processing and disposal stage (C3-4), as described previously in sections 3.2, 4.1 and 5.1. Consequently, breaking down impacts from materials into several stages will distort the benchmark values. Figure 25 shows two examples of how the flexibility of benchmark values may vary depending on life cycle stages.

Type 1 has two benchmark values - one for materials and one for operation. Here, flexibility is high within the two parameters: materials and operations. However, it is not possible to compensate for a high impact from materials by reducing operational energy or vice versa, as each of these have their own benchmark value. This affects the use of photovoltaic modules, for example, which shift impacts from operational energy use (B6) to materials (A1-3, B4 and C3-4).

Type 2 is the fully flexible benchmark value, with only one single benchmark value for the total environmental impacts from the building. This flexibility allows high impacts within individual life cycle stages, as long as this is counterbalanced by a lower impact in other life cycle stages.

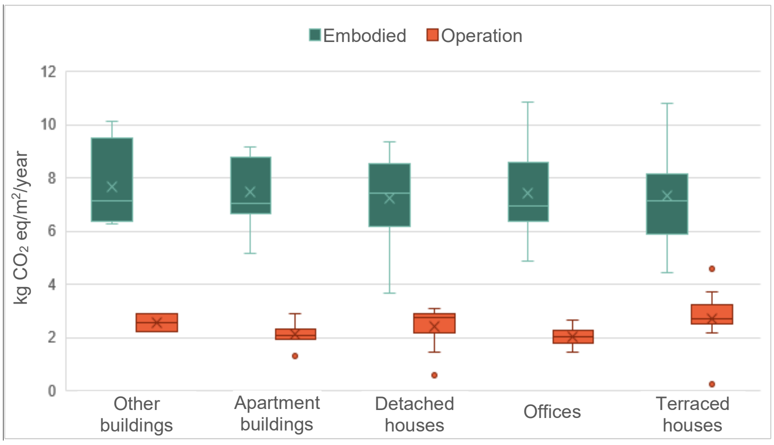



**FIGURE 25.** Examples of division into flexible and separate benchmark values in relation to life cycle stages. Type 1 is divided into two separate benchmark values: One for impacts from materials (embodied) and one for impacts from operations. Type 2 is the flexible benchmark value with only one benchmark value covering the total GWP of the building. The figure only includes life cycle stages included in this report.

## 7.2 Benchmark values based on LCA of 60 case buildings

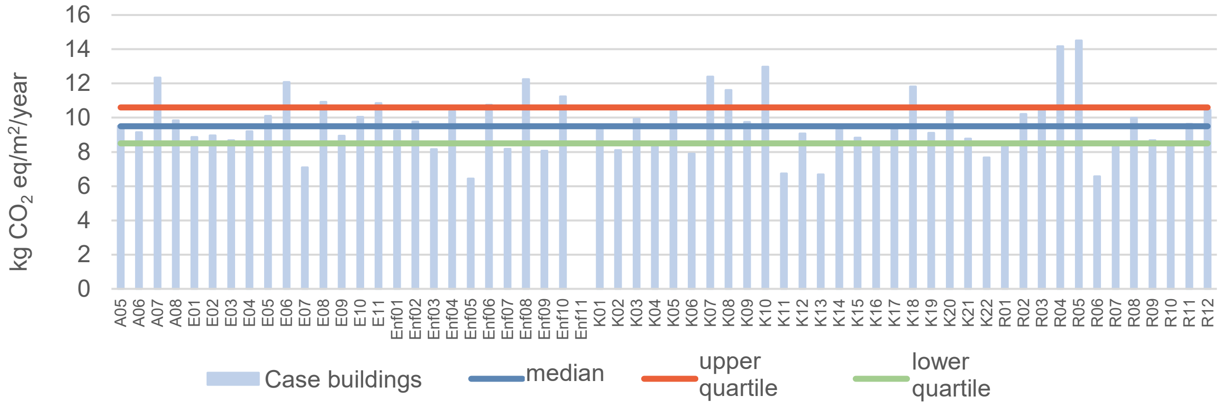
Table 7 shows the benchmark values results for all life cycle stages, both separately for materials and operation, and overall. Furthermore, it shows the three levels of ambition described above, corresponding to the median, the upper and the lower quartile for a 50-year and an 80-year reference study period. As mentioned above, there are advantages and disadvantages in the different approaches to developing benchmark values. In Sweden, focus is only on upfront carbon emissions, i.e. modules A1-A5, whereas most other countries currently developing the LCA method focus on the entire life cycle (stages A, B and C). Based on how the data material is presented upfront, with storage of biogenic carbon in stage A and release in stage C, a division of the benchmark values based on life cycle stages will distort the impact results. Consequently, separate benchmark values are not specified for these stages.

**TABLE 7.** Benchmark values are broken down by varying levels of ambition and different life cycle stages.

| | Benchmark values [kg $CO_2$ eq/m$^2$/year] | | | |
|---|---|---|---|---|
| | **Data source** | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| **50 years** | *Lower quartile* | 1.9 | 6.3 | 8.5 |
| | *Median* | 2.3 | 7.1 | 9.5 |
| | *Upper quartile* | 2.7 | 8.5 | 10.6 |
| **80 years** | *Lower quartile* | 1.8 | 5.1 | 6.9 |
| | *Median* | 2.0 | 5.7 | 8.0 |
| | *Upper quartile* | 2.5 | 6.8 | 8.9 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input modules. The results have been adjusted for missing data on technical installations (see section 3.2).

Figure 26 shows suggestions for benchmark values for all modules (including operational energy use), specifying the median value, as well as the upper and lower quartiles. The figure also shows that several buildings range considerably below the lower quartile in both a 50-year and an 80-year reference study period. These buildings can therefore also be included as benchmarks for buildings of the future. Results for the individual case buildings are in Annex IV.



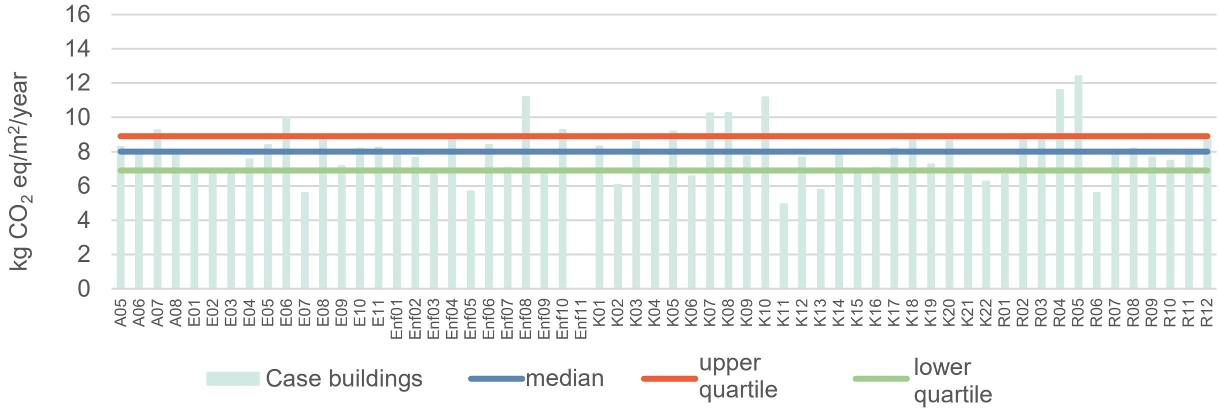




**FIGURE 26.** Benchmark values for buildings illustrated for case buildings. The figure shows the benchmark values for the total impacts from the building (all modules) per square metre of gross floor area and year over a 50-year reference study period (top) and an 80-year reference study period (bottom).

## 7.3 Benchmark-value updates

The benchmark values are based on a specific period of time, and therefore they constitute a snapshot of the situation. It is crucial that the benchmark values are updated regularly in line with technical developments, and in line with increased levels of knowledge. It is likely that more cases will be available with time, and that these can therefore help form a better data basis. Moreover, the data on environmental impacts of materials will also change as energy production is converted. This means that, in time, it will be possible to expand focus to include other environmental indicators than the GWP. More indicators would be a step towards a full picture of the total environmental impact and resource consumption, and they would also prevent possible shifts of the burdens from one environmental indicator to another.

This stresses the importance of ensuring that benchmark values are updated in accordance with general developments in Danish building and construction. In order to maintain strong incentives in the transition of the environmental impact of buildings, an important signal will be to tighten benchmark values in line with developments. If the sector follows the benchmark values for a 50-year or 80-year reference study period, building and construction can be moved towards a lower climate footprint and a more sustainable sector, and it can contribute to the goal of reducing global carbon emissions. Similarly, it will be possible to reduce the impact for other environmental indicators and resource consumption if relevant benchmark values are determined for these.

In order to benefit from LCA of buildings in the future, it is vital to develop a strategy for gathering experience and subsequent evaluation, so that the benchmark values can be updated if necessary.

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# ANNEX I: DESCRIPTION OF CASE BUILDINGS

Table 8 shows the 60 the case buildings and the related codes as well as the overall characteristics.

**TABLE 8.** Summary of the data basis for the five building types, broken down by the individual case buildings.

| | Code | Source | Energy class | Photovoltaics | Area[1] | Type of construction[2] | Weight [kg][3] |
|---|---|---|---|---|---|---|---|
| **Detached houses** | Enf01 | SBi | 2015 | - | Small | Heavy | 91416 |
| | Enf02 | SBi | 2015 | - | Small | Heavy | 210289 |
| | Enf03 | SBi | 2015 | - | Small | Light | 44656 |
| | Enf04 | SBi | 2015 | - | Small | Heavy | 133246 |
| | Enf05 | External | 2015 | - | Small | Light | 30907 |
| | Enf06 | External | 2015 | - | Small | Heavy | 202899 |
| | Enf07 | SBi | 2015 | - | Small | Heavy | 220505 |
| | Enf08 | SBi | 2015 | - | Small | Heavy | 145838 |
| | Enf09 | SBi | 2020 | - | Small | Light | 164589 |
| | Enf10 | SBi | 2015 | - | Small | Heavy | 227346 |
| | Enf11 | SBi | 2020 | X | Small | Heavy | 174504 |
| **Terraced houses** | R01 | DGNB | 2020 | X | Medium | Heavy | 4409517 |
| | R02 | DGNB | 2020 | X | Medium | Light | 904031 |
| | R03 | DGNB | 2015 | - | Medium | Heavy | 2541191 |
| | R04 | DGNB | 2015 | X | Medium | Heavy | 2365103 |
| | R05 | DGNB | 2015 | X | Medium | Heavy | 2553707 |
| | R06 | DGNB | 2015 | - | Medium | Light | 2268074 |
| | R07 | DGNB | 2015 | - | Medium | Light | 437341 |
| | R08 | SBi | 2015 | X | Medium | Heavy | 6139587 |
| | R09 | SBi | 2015 | - | Medium | Light | 2455827 |
| | R10 | SBi | 2015 | - | Medium | Light | 1888550 |
| | R11 | SBi | 2015 | - | Medium | Heavy | 2158829 |
| | R12 | DGNB | 2015 | X | Small | Light | 1005821 |
| **Apartment buildings** | E01 | DGNB | 2015 | X | Large | Heavy | 19844609 |
| | E02 | DGNB | 2020 | X | Large | Heavy | 17364661 |
| | E03 | DGNB | 2015 | X | Large | Heavy | 18219218 |
| | E04 | DGNB | 2020 | X | Large | Heavy | 21141499 |
| | E05 | DGNB | 2020 | X | Medium | Heavy | 5925821 |
| | E06 | DGNB | 2010 | X | Medium | Heavy | 5008972 |
| | E07 | DGNB | 2015 | - | Medium | Light | 3219710 |
| | E08 | DGNB | 2020 | X | Medium | Heavy | 9324872 |
| | E09 | SBi | 2015 | X | Large | Heavy | 27004694 |
| | E10 | External | 2015 | - | Medium | Heavy | 5561688 |
| | E11 | External | 2015 | - | Medium | Light | 3132188 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Offices** | K01 | DGNB | 2015 | X | Medium | Heavy | 6011991 |
| | K02 | DGNB | 2015 | X | Large | Heavy | 68481085 |
| | K03 | DGNB | 2020 | X | Medium | Heavy | 13429735 |
| | K04 | DGNB | 2020 | X | Medium | Heavy | 8566145 |
| | K05 | DGNB | 2015 | X | Medium | Heavy | 4312283 |
| | K06 | DGNB | 2015 | X | Large | Heavy | 15463761 |
| | K07 | DGNB | 2020 | X | Medium | Heavy | 6038115 |
| | K08 | DGNB | 2020 | X | Medium | Heavy | 1738747 |
| | K09 | DGNB | 2015 | X | Large | Heavy | 12999353 |
| | K10 | DGNB | 2015 | X | Medium | Heavy | 8528219 |
| | K11 | DGNB | 2015 | - | Large | Heavy | 43620490 |
| | K12 | DGNB | 2010 | - | Medium | Heavy | 8209042 |
| | K13 | DGNB | 2020 | X | Large | Heavy | 11569725 |
| | K14 | DGNB | 2020 | X | Medium | Heavy | 7270518 |
| | K15 | DGNB | 2015 | X | Medium | Heavy | 12053227 |
| | K16 | SBi | 2020 | X | Large | Heavy | 16058565 |
| | K17 | DGNB | 2020 | X | Medium | Heavy | 1819736 |
| | K18 | DGNB | 2015 | - | Medium | Heavy | 1114688 |
| | K19 | DGNB | 2015 | - | Medium | Heavy | 10383816 |
| | K20 | DGNB | 2015 | X | Large | Heavy | 16812703 |
| | K21 | DGNB | 2020 | X | Large | Heavy | 23658957 |
| | K22 | DGNB | 2020 | X | Medium | Heavy | 9654780 |
| **Other buildings** | A05 | External | 2015 | X | Large | Heavy | 28084219 |
| | A06 | External | 2015 | X | Large | Light | 23475460 |
| | A07 | SBi | 2020 | X | Medium | Heavy | 12207764 |
| | A08 | SBi | 2015 | X | Large | Heavy | 27764263 |

[1] Area is shown in categories small (<1000 $m^2$), medium (1000-10,000 $m^2$) and the large (> 10,000 $m^2$)
[2] Heavy buildings are defined as having load-bearing structures with internal walls or concrete elements, while light buildings have load-bearing structures with skeleton constructions.
[3] Amounts do not include replacements of building parts.

# ANNEX II: ADJUSTMENT FOR LACK OF DATA FOR THE TECHNICAL INSTALLATIONS

Several of the case buildings do not have detailed data on the technical installations, and this has been adjusted for. This section describes how the results have been adjusted for incomplete data so that they contain environmental impacts corresponding to the technical installations. Technical installations do not include photovoltaic modules, as data for these are adequate for the relevant cases and therefore it has not been necessary to adjust for incomplete data.

Impacts from technical installations are shown in figure 27 with a 50-year reference study period. The figure shows that installations have only been included to a limited extent for many of the case of buildings. In other words, many the case of buildings do not have data for water and drainage installations. The large spread in results for installation groups is also due to the varying completeness of data. This means that some cases contain supply, pipework and user installations for the various installations, while others include only supply. If incomplete data is not taken into account, installations account for less than 10% of the buildings' total GWP of materials in the existing data from the case buildings. The percentages are illustrated in figure 27 for a 50-year reference study period.

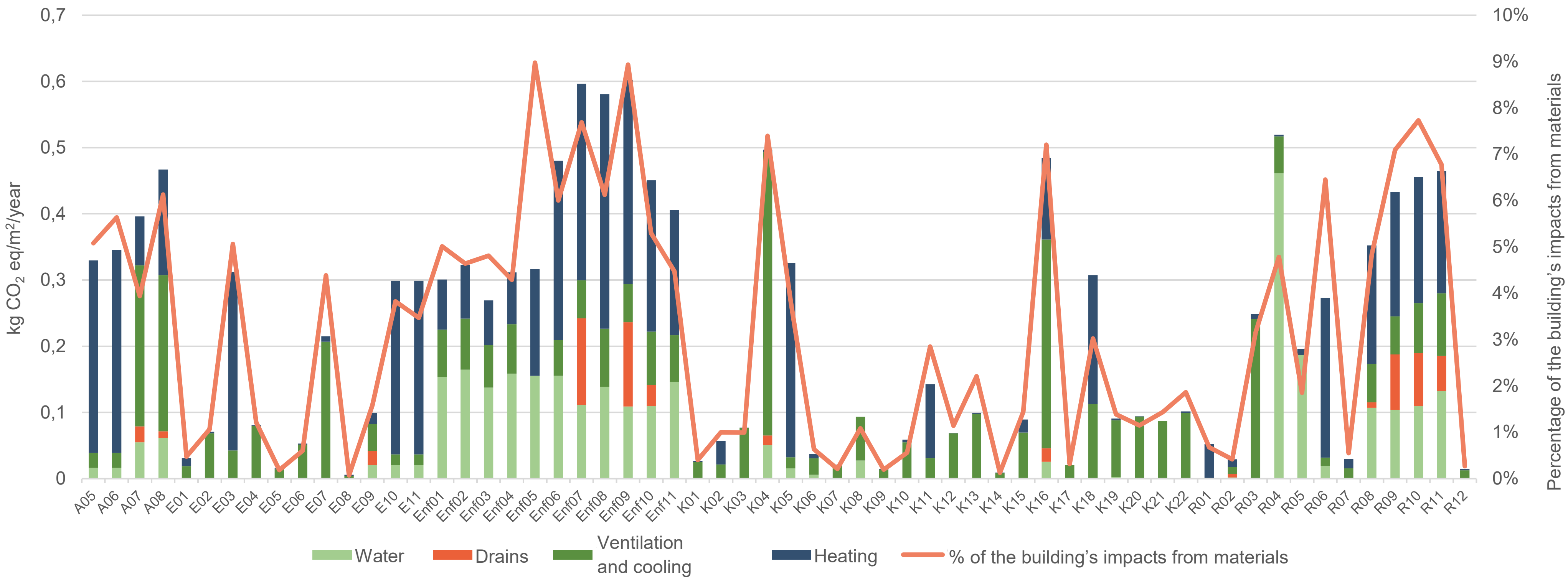



**FIGURE 27.** Reported (incomplete) technical installations from all cases, as well as the percentage from technical installations of the total impacts from materials over a 50-year reference study period. The columns refer to the axis on the left, and show the size of GWP of the technical installations. The curve refers to the axis to the right and shows the percentage of the technical installations in relation to the building's overall GWP.

For a more accurate presentation of the size of the GWP of the installations, there is a need to select the data with most information about the installation groups. Each of the four installation groups can be divided into sub-groups. Table 9 shows the relevant sub-groups, and the number of cases including materials from the sub-groups. On the basis of this, projects are selected that include the most important sub-groups and can therefore be considered as a “complete” installation group. It has not been crucial always to include water pipes for the Heating group, as the number of cases would otherwise be too limited. The impacts from the selected cases are shown in figures 28-31. The impacts from water installations are shown in figure 28. The selected case buildings primarily consist of homes, and their impacts have very little spread. Figure 29 shows that the GWP of installations for ventilation/cooling is considerably higher for office buildings and other buildings than for detached houses and terraced houses. This corresponds well with the fact that there are usually stricter air-change requirements for offices and institutions than for homes. This means installations and piping systems are larger in offices and institutions than in homes. There are large differences in impacts from ventilation between the two apartment buildings. Figure 30 shows that impacts from heating installations are generally high for all types of building. Conversely, the impact from drains is low in figure 31. There is a large spread in the results, and this reflects that there is still a large difference between how much is included in the individual cases.

**TABLE 9.** Cases with completed material data for different installation groups.

| Groups | Number of projects with completed groups | Sub-groups |
|---|---|---|
| **Drains** | 11 | Waste pipes |
| | | Downpipes from roof |
| **Water** | 14 | Hot-water tanks |
| | | Water pipes |
| **Heating** | 22 | Supply installations |
| | | Heating pipes |
| | | Underfloor heating/radiators |
| **Ventilation and cooling** | 18 | Ventilation system + possibly cooling |
| | | Ventilation ducts |

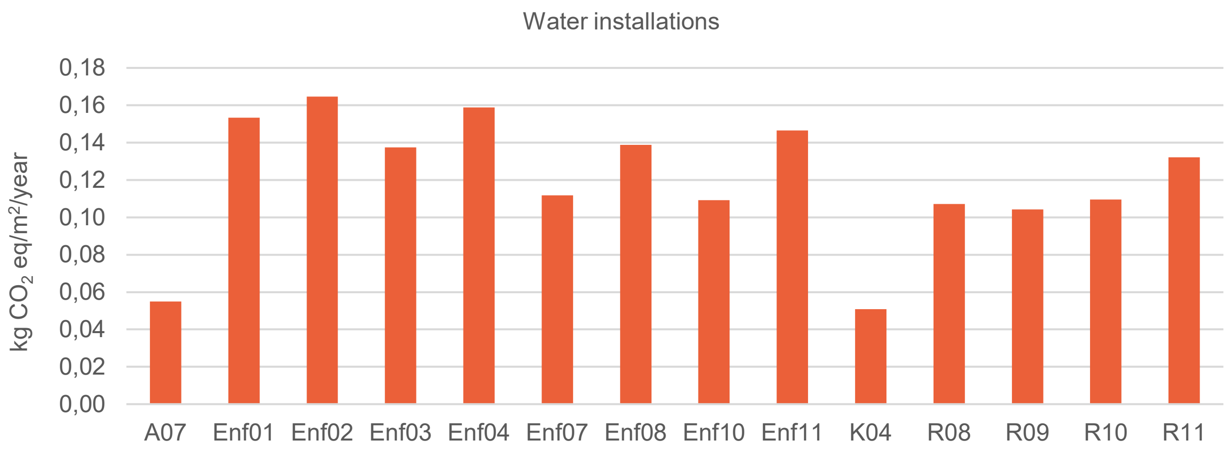



**FIGURE 28.** Impacts from water installations in case buildings for a 50-year reference study period where the installation group is completed.

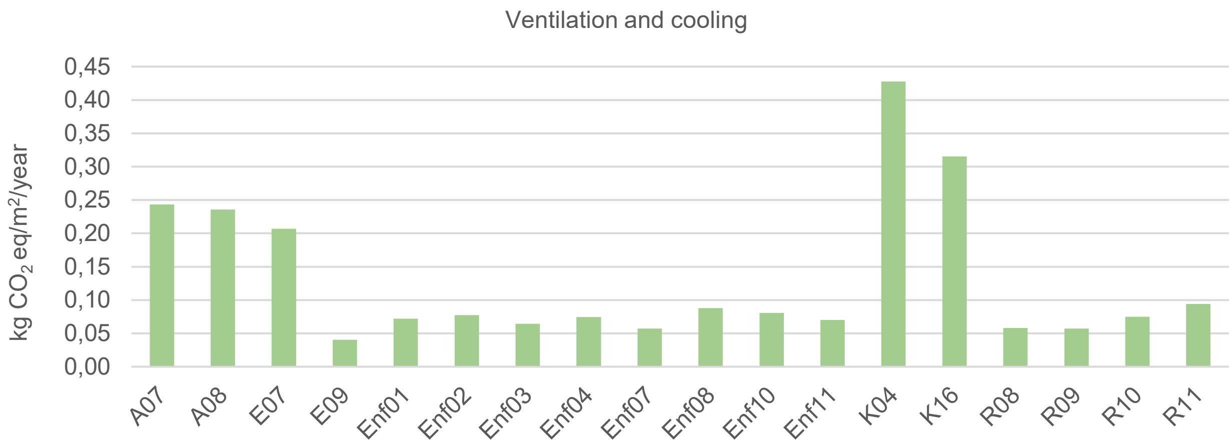



**FIGURE 29.** Impacts from ventilation and cooling installations in case buildings for a 50-year reference study period where the installation group is completed.

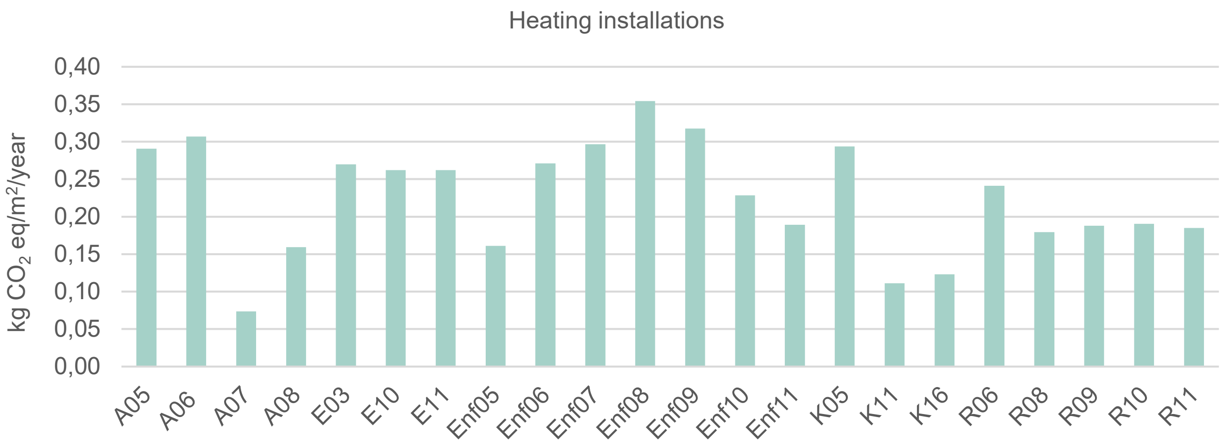



**FIGURE 30.** Impacts from heating installations in case buildings for a 50-year reference study period where the installation group is completed.

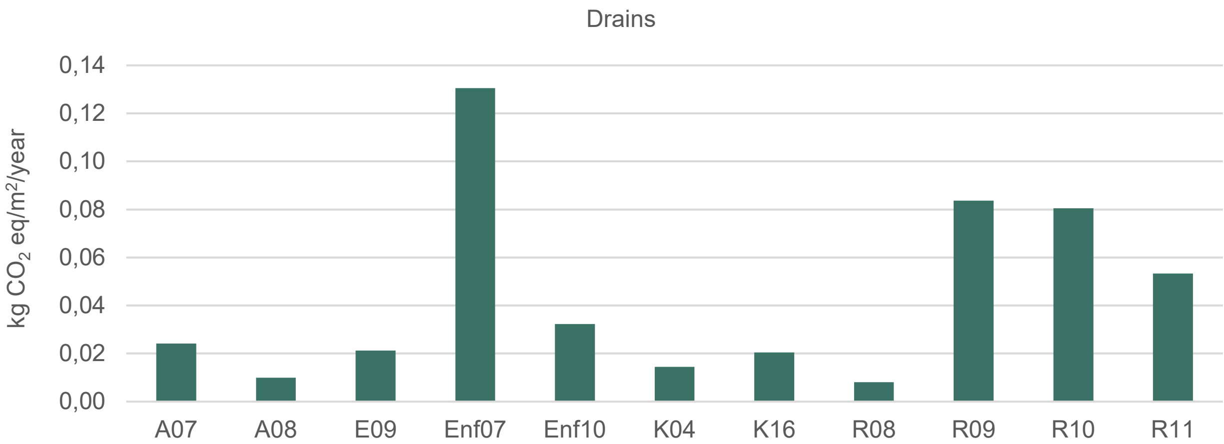



**FIGURE 31.** Impacts from drainage installations in case buildings for a 50-year reference study period where the installation group is completed.

The impact of the completed installation groups can form the basis for generic values which may be used in projects where there is no information on quantities of materials for installations. The report contains the generic values used for all the case buildings. The median impacts are calculated on the basis of the impacts for the completed installation groups (table

2) and used as generic values instead of the specific impacts of technical installations. Figure 32 shows the results from the case buildings with the calculated median value impact (generic value) for the technical installations compared with the case-specific impact for the technical installations (as also shown in figure 27).

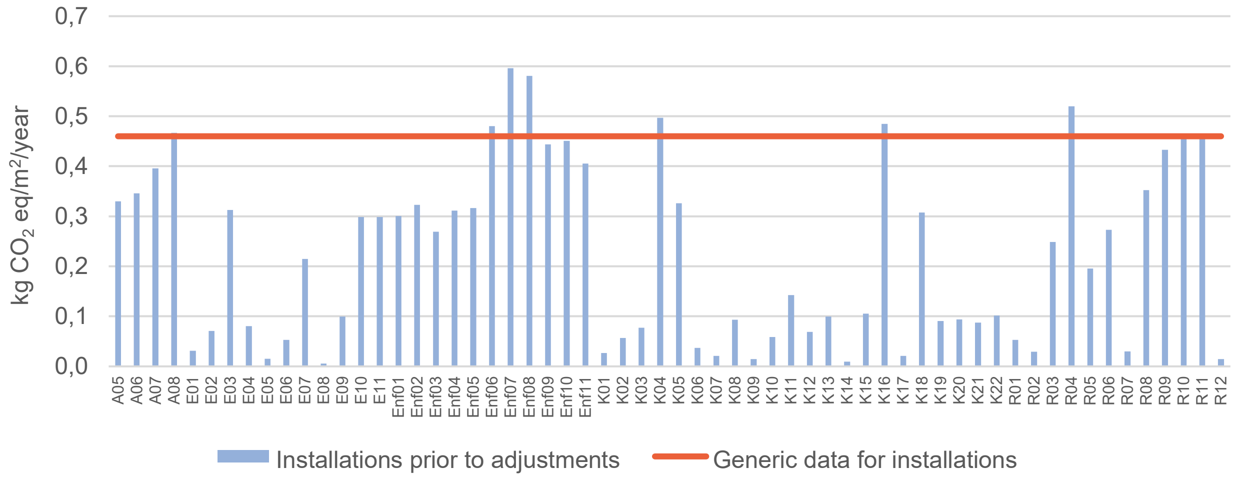


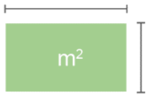

**FIGURE 32.** Median value impact (generic data) for the technical installations in relation to the case-specific impact for installations.

Generic values for the technical installations for an 80-year reference study period are found in the same way as in this section. As this method is the same for a 50-year and 80-year reference study period, this is not reviewed any further for the 80-year reference study period. The median value impact for case buildings for an 80-year reference study period is in table 2 in section 3.2.

# ANNEX III: USE OF ESTIMATED LCA

In the early design phases of a building in which the design has not been completely finalised, estimates for selection and quantities of materials are used to differing degrees. This section examines an approach to estimated LCA in the LCAbyg tool. On the basis of six case buildings that are modelled with an estimated and a detailed approach, the study examines how close the tool for estimated LCA is to the result for the detailed LCA. The analysis has no influence on the benchmark values in this report, but it shows the influences on the result from using functions in LCAbyg for an estimated LCA.

In LCAbyg version 4.0 (beta), tools have been developed to help the user to obtain a complete building model, despite a lack of project information. These tools are a catalogue of examples with generic structural designs, and a calculation aid to estimate the quantities of building parts, see figure 33. Using these tools usually results in a prudent estimate of the quantities of materials in building parts, and this gives an indication of the building's expected environmental footprint.




**Calculation aid**
Estimation of quantities
for building parts

**Catalogue of examples**
Catalogue with generic
structural designs

**FIGURE 33.** The LCAbyg tool has functions to perform LCA in early design phases. The functions include a catalogue of examples and a calculation aid.

This section examines how use of the catalogue of examples and the calculation aid to estimate materials consumption affects the results of the LCA. The outset for this is in six different case buildings modelled at three different levels of accuracy described as estimated, adjusted and detailed. Accuracy means the precision of an LCA in relation to the actual material type and quantities in the building project. The level of accuracy is elaborated in table 10, in which the three levels are differentiated in the way they estimate the type of materials, thickness of materials, as well as the area the different building parts cover. "Specific" in table 10 refers to the actual structural design as well as the actual quantities of building parts based on drawings. Table 10 also shows the number of case buildings modelled for each level of accuracy.

**TABLE 10.**Table of levels of accuracy for case buildings and the number of case buildings modelled for each level of accuracy.

| | | Estimated | Adjusted | Detailed |
|---|---|---|---|---|
| **Structural design** | **Material type** | Catalogue of examples in LCAbyg | Specific | Specific |
| | **Thickness of layer** | Catalogue of examples in LCAbyg | Specific | Specific |
| **Quantities of building parts** | **Areas** | Calculation aid in LCAbyg | Calculation aid in LCAbyg | Specific |

Figure 34 shows the results of the analysis. It demonstrates that the accuracy of the LCA influences the overall GWP of the building. The results show that, for all the case buildings, the detailed scenarios have the lowest GWP and the estimated scenario has the highest GWP. The estimated scenario is up to 16% higher than the detailed, but in four out of the six cases the estimate is within 11% of the detailed. In most situations, the cases according to the adjusted scenarios have an impact between the impact found with the estimated scenario and that found with the detailed scenario. The results here are within 18% of the detailed.

The strong impact from the estimated scenario was expected, as the catalogue of examples is conservative with respect to the thickness of the insulation and other material layers. Furthermore, the calculation aid is conservative in estimating the area the building part covers because it does not take account of the overlap of walls, for example. Indication of the exact areas instead of the areas calculated in the calculation aid in the tool can reduce environmental impacts by up to 18%.

In three cases, the impact of the adjusted scenario is higher than the estimated scenario. This is because the structural design in the detailed scenario deviates significantly from those available in the catalogue of examples, including thickness and type of insulation, and the load-bearing structures. The reason for this is that the buildings have thicker insulation in the basement slab and external walls than in the catalogue of examples. Furthermore, several cases use a type of insulation with higher GWP than exists in the catalogue of examples: e.g. pressure insulation in the roof, which has a considerably higher GWP than similar insulation with low density. The thickness and strength of concrete structures in the case buildings also differ from the catalogue of examples in some cases.

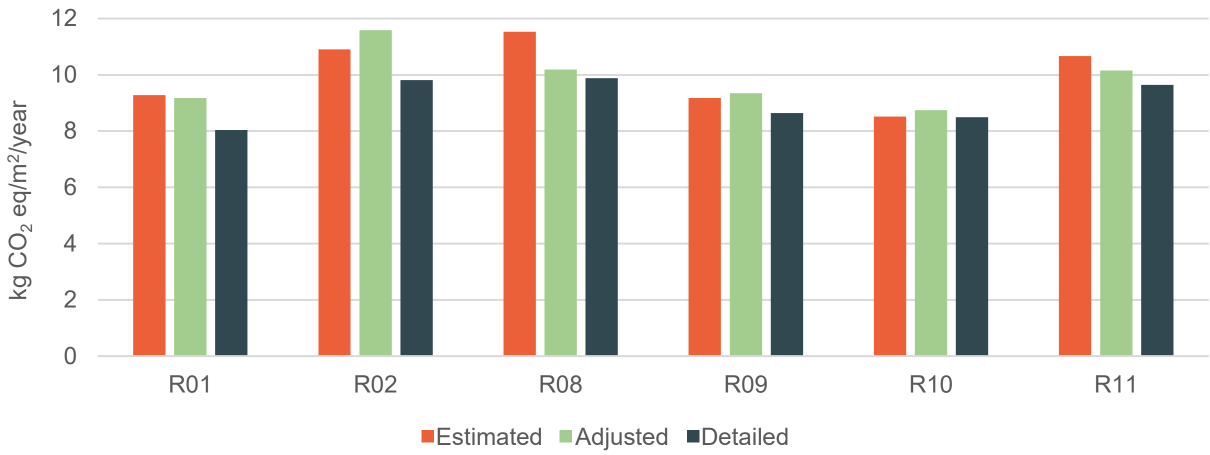



**FIGURE 34.** Breakdown of the total impacts for materials and operation for the three levels of accuracy for a 50-year reference study period

In most situations, the estimated LCAs provide a conservative estimate of the detailed LCA. However, on the basis of this analysis, as well as previous similar analyses (Zimmermann, Kanafani, Rasmussen, & Birgisdottir, 2019) it is clear that it is important to be aware of the quantity and type of insulation when making an estimated LCA. This is particularly important if there are plans to construct a building with more insulation than the standard, or if pressure insulation is to be used. Load-bearing elements, including concrete structures, should also be stated at the correct strength and quantity as soon as these figures are available in the project.

This analysis shows that the catalogue of examples and the calculation aid can be used in the early design phase to provide an idea of the size of the environmental impacts of a given project. Later in the project, structural designs and areas should be adjusted to calculate the exact environmental impact corresponding to the detailed LCA.

# ANNEX IV: DETAILED LCA RESULTS WITH 50-YEAR REFERENCE STUDY PERIOD

Tables 11 to 19 present the environmental impacts for all modules of the 60 case buildings with a 50-year reference study period as well as for all categories of environmental impact included in LCAbyg version 4.0 (beta):

- Global Warming Potential (GWP, kg $CO_2$ equivalent)
- Depletion Potential of the Stratospheric Ozone Layer (ODP, in kg R11 eq)
- Acidification Potential (AP in kg $SO_2$ eq)
- Eutrophication Potential (EP, in kg $PO_4$ eq)
- Formation Potential of Tropospheric Ozone Photochemical Oxidants (POCP, in kg ethylene eq)
- Abiotic Depletion Potential for Non-fossil Resources (ADPe, in SP eq)
- Abiotic Depletion Potential for Fossil Resources (ADPf, in MJ)
- Total Use of Primary Energy (PEtot, in MJ or kWh)
- Use of Renewable Secondary Fuels (SEK, in MJ or kWh)

## Results for 50-year reference study period

**TABLE 11.** Results of cases for GWP

| | kg $CO_2$ eq/m$^2$/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 3.08E+00 | 6.16E+00 | 9.24E+00 |
| Enf02 | 2.66E+00 | 7.10E+00 | 9.76E+00 |
| Enf03 | 2.38E+00 | 5.79E+00 | 8.17E+00 |
| Enf04 | 2.98E+00 | 7.40E+00 | 1.04E+01 |
| Enf05 | 2.78E+00 | 3.67E+00 | 6.45E+00 |
| Enf06 | 2.78E+00 | 7.98E+00 | 1.08E+01 |
| Enf07 | 5.64E-01 | 7.62E+00 | 8.18E+00 |
| Enf08 | 2.89E+00 | 9.36E+00 | 1.22E+01 |
| Enf09 | 1.46E+00 | 6.60E+00 | 8.07E+00 |
| Enf10 | 2.72E+00 | 8.52E+00 | 1.12E+01 |
| Enf11 | - | 9.12E+00 | - |
| R01 | 2.21E-01 | 8.17E+00 | 8.39E+00 |
| R02 | 2.78E+00 | 7.44E+00 | 1.02E+01 |
| R03 | 2.48E+00 | 8.11E+00 | 1.06E+01 |
| R04 | 3.36E+00 | 1.08E+01 | 1.42E+01 |
| R05 | 3.70E+00 | 1.08E+01 | 1.45E+01 |
| R06 | 2.16E+00 | 4.42E+00 | 6.58E+00 |
| R07 | 2.77E+00 | 5.80E+00 | 8.57E+00 |
| R08 | 2.60E+00 | 7.39E+00 | 9.99E+00 |
| R09 | 2.55E+00 | 6.13E+00 | 8.67E+00 |
| R10 | 2.60E+00 | 5.90E+00 | 8.50E+00 |
| R11 | 2.78E+00 | 6.85E+00 | 9.63E+00 |
| R12 | 4.58E+00 | 5.87E+00 | 1.05E+01 |
| E01 | 1.91E+00 | 6.95E+00 | 8.86E+00 |
| E02 | 1.92E+00 | 7.05E+00 | 8.96E+00 |
| E03 | 2.37E+00 | 6.32E+00 | 8.68E+00 |
| E04 | 2.19E+00 | 7.03E+00 | 9.21E+00 |
| E05 | 1.30E+00 | 8.80E+00 | 1.01E+01 |
| E06 | 2.91E+00 | 9.17E+00 | 1.21E+01 |
| E07 | 1.95E+00 | 5.14E+00 | 7.09E+00 |
| E08 | 2.32E+00 | 8.61E+00 | 1.09E+01 |
| E09 | 2.31E+00 | 6.64E+00 | 8.95E+00 |
| E10 | 2.07E+00 | 7.97E+00 | 1.00E+01 |
| E11 | 2.07E+00 | 8.77E+00 | 1.08E+01 |
| K01 | 2.38E+00 | 7.14E+00 | 9.52E+00 |
| K02 | 2.03E+00 | 6.09E+00 | 8.11E+00 |
| K03 | 1.82E+00 | 8.13E+00 | 9.94E+00 |
| K04 | 1.68E+00 | 6.68E+00 | 8.36E+00 |
| K05 | 2.06E+00 | 8.64E+00 | 1.07E+01 |
| K06 | 1.64E+00 | 6.26E+00 | 7.90E+00 |
| K07 | 2.11E+00 | 1.03E+01 | 1.24E+01 |
| K08 | 2.65E+00 | 8.96E+00 | 1.16E+01 |
| K09 | 1.91E+00 | 7.84E+00 | 9.75E+00 |
| K10 | 2.14E+00 | 1.08E+01 | 1.30E+01 |
| K11 | 1.42E+00 | 5.32E+00 | 6.75E+00 |
| K12 | 2.66E+00 | 6.41E+00 | 9.07E+00 |
| K13 | 1.83E+00 | 4.86E+00 | 6.69E+00 |
| K14 | 1.82E+00 | 7.75E+00 | 9.56E+00 |
| K15 | 2.26E+00 | 6.58E+00 | 8.84E+00 |
| K16 | 1.68E+00 | 6.70E+00 | 8.37E+00 |
| K17 | 2.61E+00 | 6.98E+00 | 9.59E+00 |
| K18 | 1.49E+00 | 1.03E+01 | 1.18E+01 |
| K19 | 2.21E+00 | 6.90E+00 | 9.11E+00 |
| K20 | 2.02E+00 | 8.53E+00 | 1.06E+01 |
| K21 | 2.32E+00 | 6.46E+00 | 8.77E+00 |
| K22 | 1.87E+00 | 5.80E+00 | 7.67E+00 |
| A05 | 2.90E+00 | 6.62E+00 | 9.52E+00 |
| A06 | 2.90E+00 | 6.25E+00 | 9.15E+00 |
| A07 | 2.22E+00 | 1.01E+01 | 1.23E+01 |
| A08 | 2.23E+00 | 7.61E+00 | 9.84E+00 |
| Lower quartile | 1.91E+00 | 6.27E+00 | 8.50E+00 |
| Median | 2.26E+00 | 7.07E+00 | 9.52E+00 |
| Upper quartile | 2.72E+00 | 8.53E+00 | 1.06E+01 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 12.** Results of cases for ODP

| | kg R11 eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.42E-10 | 3.82E-08 | 3.85E-08 |
| Enf02 | 2.12E-10 | 5.16E-08 | 5.19E-08 |
| Enf03 | 1.95E-10 | 8.87E-08 | 8.89E-08 |
| Enf04 | 2.19E-10 | 4.38E-08 | 4.40E-08 |
| Enf05 | 2.23E-10 | 1.13E-07 | 1.14E-07 |
| Enf06 | 2.23E-10 | 4.51E-08 | 4.53E-08 |
| Enf07 | 2.33E-11 | 1.07E-07 | 1.07E-07 |
| Enf08 | 2.28E-10 | 1.85E-07 | 1.85E-07 |
| Enf09 | 1.15E-10 | 7.98E-08 | 8.00E-08 |
| Enf10 | 2.17E-10 | 1.31E-07 | 1.32E-07 |
| Enf11 | - | 1.18E-07 | - |
| R01 | 9.14E-12 | 1.33E-08 | 1.33E-08 |
| R02 | 2.23E-10 | 3.53E-08 | 3.56E-08 |
| R03 | 1.96E-10 | 9.74E-09 | 9.93E-09 |
| R04 | 2.30E-10 | 1.40E-08 | 1.42E-08 |
| R05 | 2.60E-10 | 1.76E-08 | 1.79E-08 |
| R06 | 1.71E-10 | 4.59E-08 | 4.60E-08 |
| R07 | 2.16E-10 | 3.64E-08 | 3.66E-08 |
| R08 | 2.07E-10 | 8.64E-08 | 8.66E-08 |
| R09 | 2.10E-10 | 6.23E-08 | 6.25E-08 |
| R10 | 2.07E-10 | 1.05E-07 | 1.05E-07 |
| R11 | 2.22E-10 | 1.34E-07 | 1.34E-07 |
| R12 | 3.89E-10 | 4.82E-08 | 4.86E-08 |
| E01 | 1.52E-10 | 2.27E-08 | 2.29E-08 |
| E02 | 1.53E-10 | 1.13E-08 | 1.14E-08 |
| E03 | 1.91E-10 | 1.49E-08 | 1.50E-08 |
| E04 | 1.78E-10 | 1.25E-08 | 1.26E-08 |
| E05 | 1.12E-10 | 2.19E-08 | 2.20E-08 |
| E06 | 2.28E-10 | 4.92E-09 | 5.15E-09 |
| E07 | 1.53E-10 | 1.07E-07 | 1.07E-07 |
| E08 | 1.91E-10 | 1.15E-08 | 1.17E-08 |
| E09 | 1.79E-10 | 9.67E-09 | 9.85E-09 |
| E10 | 1.68E-10 | 2.47E-08 | 2.49E-08 |
| E11 | 1.68E-10 | 5.06E-08 | 5.08E-08 |
| K01 | 1.83E-10 | 8.62E-09 | 8.80E-09 |
| K02 | 1.48E-10 | 1.15E-08 | 1.16E-08 |
| K03 | 1.33E-10 | 6.98E-08 | 7.00E-08 |
| K04 | 1.26E-10 | 1.04E-08 | 1.05E-08 |
| K05 | 1.52E-10 | 2.27E-08 | 2.29E-08 |
| K06 | 1.15E-10 | 1.04E-08 | 1.05E-08 |
| K07 | 1.59E-10 | 1.94E-08 | 1.96E-08 |
| K08 | 1.89E-10 | 9.37E-09 | 9.55E-09 |
| K09 | 1.35E-10 | 9.29E-09 | 9.42E-09 |
| K10 | 1.51E-10 | 2.06E-08 | 2.08E-08 |
| K11 | 8.67E-11 | 1.90E-08 | 1.91E-08 |
| K12 | 1.94E-10 | 5.91E-09 | 6.10E-09 |
| K13 | 1.32E-10 | 5.93E-09 | 6.07E-09 |
| K14 | 1.29E-10 | 1.24E-08 | 1.26E-08 |
| K15 | 1.69E-10 | 1.17E-08 | 1.18E-08 |
| K16 | 1.19E-10 | 9.79E-09 | 9.91E-09 |
| K17 | 1.81E-10 | 9.64E-09 | 9.82E-09 |
| K18 | 6.16E-11 | 8.45E-09 | 8.51E-09 |
| K19 | 1.55E-10 | 3.65E-08 | 3.66E-08 |
| K20 | 1.43E-10 | 1.91E-08 | 1.92E-08 |
| K21 | 1.64E-10 | 1.03E-08 | 1.05E-08 |
| K22 | 1.33E-10 | 8.22E-09 | 8.36E-09 |
| A05 | 2.15E-10 | 2.64E-08 | 2.66E-08 |
| A06 | 2.15E-10 | 2.66E-08 | 2.68E-08 |
| A07 | 1.66E-10 | 1.34E-08 | 1.35E-08 |
| A08 | 1.66E-10 | 1.05E-08 | 1.06E-08 |
| Lower quartile | 1.43E-10 | 1.04E-08 | 1.05E-08 |
| Median | 1.71E-10 | 2.00E-08 | 1.96E-08 |
| Upper quartile | 2.15E-10 | 5.00E-08 | 4.86E-08 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 13.** Results of cases for AP

| | kg $SO_2$ eq/m$^2$/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 1.34E-02 | 1.83E-02 | 3.17E-02 |
| Enf02 | 1.10E-02 | 1.74E-02 | 2.84E-02 |
| Enf03 | 8.77E-03 | 2.54E-02 | 3.41E-02 |
| Enf04 | 1.58E-02 | 1.58E-02 | 3.16E-02 |
| Enf05 | 1.12E-02 | 1.35E-02 | 2.47E-02 |
| Enf06 | 1.12E-02 | 1.93E-02 | 3.05E-02 |
| Enf07 | 6.48E-03 | 1.48E-02 | 2.13E-02 |
| Enf08 | 1.24E-02 | 2.54E-02 | 3.78E-02 |
| Enf09 | 6.43E-03 | 1.73E-02 | 2.38E-02 |
| Enf10 | 1.11E-02 | 2.09E-02 | 3.20E-02 |
| Enf11 | - | 2.41E-02 | - |
| R01 | 2.54E-03 | 2.98E-02 | 3.23E-02 |
| R02 | 1.12E-02 | 2.55E-02 | 3.67E-02 |
| R03 | 1.04E-02 | 2.44E-02 | 3.49E-02 |
| R04 | 8.43E-03 | 3.13E-02 | 3.97E-02 |
| R05 | 1.00E-02 | 3.00E-02 | 4.00E-02 |
| R06 | 9.17E-03 | 1.13E-02 | 2.05E-02 |
| R07 | 1.23E-02 | 1.37E-02 | 2.60E-02 |
| R08 | 1.07E-02 | 1.67E-02 | 2.73E-02 |
| R09 | 9.19E-03 | 1.64E-02 | 2.56E-02 |
| R10 | 1.07E-02 | 1.79E-02 | 2.85E-02 |
| R11 | 1.13E-02 | 1.73E-02 | 2.86E-02 |
| R12 | 1.42E-02 | 1.71E-02 | 3.13E-02 |
| E01 | 8.00E-03 | 1.78E-02 | 2.58E-02 |
| E02 | 7.84E-03 | 1.55E-02 | 2.33E-02 |
| E03 | 9.33E-03 | 1.51E-02 | 2.44E-02 |
| E04 | 8.35E-03 | 1.88E-02 | 2.71E-02 |
| E05 | 3.74E-03 | 1.77E-02 | 2.15E-02 |
| E06 | 1.28E-02 | 2.19E-02 | 3.48E-02 |
| E07 | 8.41E-03 | 1.57E-02 | 2.41E-02 |
| E08 | 8.37E-03 | 2.06E-02 | 2.89E-02 |
| E09 | 1.04E-02 | 1.47E-02 | 2.51E-02 |
| E10 | 7.98E-03 | 1.69E-02 | 2.49E-02 |
| E11 | 7.98E-03 | 2.21E-02 | 3.00E-02 |
| K01 | 1.12E-02 | 2.09E-02 | 3.20E-02 |
| K02 | 1.10E-02 | 1.38E-02 | 2.48E-02 |
| K03 | 9.81E-03 | 2.21E-02 | 3.19E-02 |
| K04 | 8.44E-03 | 1.44E-02 | 2.28E-02 |
| K05 | 1.07E-02 | 2.81E-02 | 3.88E-02 |
| K06 | 9.72E-03 | 1.68E-02 | 2.65E-02 |
| K07 | 1.05E-02 | 2.19E-02 | 3.24E-02 |
| K08 | 1.52E-02 | 2.70E-02 | 4.22E-02 |
| K09 | 1.12E-02 | 2.07E-02 | 3.19E-02 |
| K10 | 1.25E-02 | 2.79E-02 | 4.05E-02 |
| K11 | 1.10E-02 | 1.30E-02 | 2.40E-02 |
| K12 | 1.45E-02 | 1.87E-02 | 3.31E-02 |
| K13 | 1.02E-02 | 1.33E-02 | 2.34E-02 |
| K14 | 1.06E-02 | 1.63E-02 | 2.69E-02 |
| K15 | 1.15E-02 | 1.49E-02 | 2.64E-02 |
| K16 | 9.72E-03 | 1.71E-02 | 2.69E-02 |
| K17 | 1.60E-02 | 1.59E-02 | 3.19E-02 |
| K18 | 1.71E-02 | 2.45E-02 | 4.16E-02 |
| K19 | 1.33E-02 | 1.60E-02 | 2.93E-02 |
| K20 | 1.17E-02 | 2.33E-02 | 3.50E-02 |
| K21 | 1.35E-02 | 1.48E-02 | 2.83E-02 |
| K22 | 1.09E-02 | 1.47E-02 | 2.56E-02 |
| A05 | 1.50E-02 | 2.14E-02 | 3.64E-02 |
| A06 | 1.50E-02 | 2.04E-02 | 3.54E-02 |
| A07 | 1.12E-02 | 2.97E-02 | 4.09E-02 |
| A08 | 1.16E-02 | 1.96E-02 | 3.11E-02 |
| Lower quartile | 9.17E-03 | 1.58E-02 | 2.57E-02 |
| Median | 1.09E-02 | 1.79E-02 | 2.94E-02 |
| Upper quartile | 1.23E-02 | 2.22E-02 | 3.42E-02 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 14.** Results of cases for EP

| | kg $PO_4$ eq/m$^2$/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.61E-03 | 2.16E-03 | 4.76E-03 |
| Enf02 | 2.08E-03 | 2.35E-03 | 4.42E-03 |
| Enf03 | 1.54E-03 | 3.56E-03 | 5.11E-03 |
| Enf04 | 3.36E-03 | 2.21E-03 | 5.57E-03 |
| Enf05 | 2.10E-03 | 2.24E-03 | 4.34E-03 |
| Enf06 | 2.10E-03 | 2.71E-03 | 4.80E-03 |
| Enf07 | 1.67E-03 | 1.95E-03 | 3.62E-03 |
| Enf08 | 2.40E-03 | 3.34E-03 | 5.74E-03 |
| Enf09 | 1.26E-03 | 2.69E-03 | 3.95E-03 |
| Enf10 | 2.08E-03 | 2.84E-03 | 4.92E-03 |
| Enf11 | - | 3.16E-03 | - |
| R01 | 6.54E-04 | 2.86E-03 | 3.52E-03 |
| R02 | 2.10E-03 | 3.12E-03 | 5.22E-03 |
| R03 | 2.00E-03 | 2.42E-03 | 4.41E-03 |
| R04 | 1.30E-03 | 3.01E-03 | 4.31E-03 |
| R05 | 1.60E-03 | 2.92E-03 | 4.52E-03 |
| R06 | 1.76E-03 | 1.70E-03 | 3.46E-03 |
| R07 | 2.41E-03 | 1.98E-03 | 4.40E-03 |
| R08 | 2.01E-03 | 2.17E-03 | 4.17E-03 |
| R09 | 1.59E-03 | 2.38E-03 | 3.98E-03 |
| R10 | 2.01E-03 | 2.79E-03 | 4.80E-03 |
| R11 | 2.12E-03 | 2.40E-03 | 4.52E-03 |
| R12 | 2.18E-03 | 2.50E-03 | 4.68E-03 |
| E01 | 1.52E-03 | 2.04E-03 | 3.56E-03 |
| E02 | 1.47E-03 | 1.95E-03 | 3.43E-03 |
| E03 | 1.71E-03 | 2.10E-03 | 3.81E-03 |
| E04 | 1.50E-03 | 2.53E-03 | 4.04E-03 |
| E05 | 5.31E-04 | 2.46E-03 | 2.99E-03 |
| E06 | 2.50E-03 | 2.65E-03 | 5.16E-03 |
| E07 | 1.63E-03 | 2.36E-03 | 3.98E-03 |
| E08 | 1.45E-03 | 2.38E-03 | 3.83E-03 |
| E09 | 2.07E-03 | 1.91E-03 | 3.98E-03 |
| E10 | 1.45E-03 | 2.27E-03 | 3.71E-03 |
| E11 | 1.45E-03 | 2.57E-03 | 4.02E-03 |
| K01 | 2.25E-03 | 2.36E-03 | 4.61E-03 |
| K02 | 2.35E-03 | 1.77E-03 | 4.12E-03 |
| K03 | 2.10E-03 | 2.49E-03 | 4.59E-03 |
| K04 | 1.76E-03 | 1.76E-03 | 3.51E-03 |
| K05 | 2.26E-03 | 3.25E-03 | 5.51E-03 |
| K06 | 2.15E-03 | 1.82E-03 | 3.98E-03 |
| K07 | 2.16E-03 | 2.79E-03 | 4.96E-03 |
| K08 | 3.33E-03 | 3.46E-03 | 6.78E-03 |
| K09 | 2.46E-03 | 2.84E-03 | 5.30E-03 |
| K10 | 2.76E-03 | 3.66E-03 | 6.43E-03 |
| K11 | 2.63E-03 | 1.69E-03 | 4.32E-03 |
| K12 | 3.10E-03 | 2.83E-03 | 5.93E-03 |
| K13 | 2.20E-03 | 1.67E-03 | 3.87E-03 |
| K14 | 2.33E-03 | 2.18E-03 | 4.52E-03 |
| K15 | 2.39E-03 | 1.86E-03 | 4.26E-03 |
| K16 | 2.14E-03 | 2.40E-03 | 4.53E-03 |
| K17 | 3.59E-03 | 2.22E-03 | 5.81E-03 |
| K18 | 4.40E-03 | 3.04E-03 | 7.44E-03 |
| K19 | 2.95E-03 | 2.26E-03 | 5.20E-03 |
| K20 | 2.57E-03 | 3.47E-03 | 6.04E-03 |
| K21 | 2.97E-03 | 1.91E-03 | 4.88E-03 |
| K22 | 2.39E-03 | 1.91E-03 | 4.30E-03 |
| A05 | 3.16E-03 | 2.85E-03 | 6.01E-03 |
| A06 | 3.16E-03 | 2.88E-03 | 6.04E-03 |
| A07 | 2.34E-03 | 3.06E-03 | 5.40E-03 |
| A08 | 2.44E-03 | 2.54E-03 | 4.98E-03 |
| Lower quartile | 1.67E-03 | 2.12E-03 | 3.99E-03 |
| Median | 2.14E-03 | 2.42E-03 | 4.53E-03 |
| Upper quartile | 2.46E-03 | 2.86E-03 | 5.22E-03 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 15.** Results of cases for POCP

| | kg ethylene eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 1.40E-03 | 3.24E-03 | 4.64E-03 |
| Enf02 | 1.04E-03 | 4.46E-03 | 5.50E-03 |
| Enf03 | 6.33E-04 | 8.89E-04 | 1.52E-03 |
| Enf04 | 2.15E-03 | 5.35E-03 | 7.50E-03 |
| Enf05 | 1.02E-03 | 1.84E-03 | 2.85E-03 |
| Enf06 | 1.02E-03 | 5.10E-03 | 6.11E-03 |
| Enf07 | 1.39E-03 | 6.98E-03 | 8.37E-03 |
| Enf08 | 1.26E-03 | 7.68E-03 | 8.94E-03 |
| Enf09 | 6.80E-04 | 4.44E-03 | 5.12E-03 |
| Enf10 | 1.03E-03 | 6.50E-03 | 7.52E-03 |
| Enf11 | - | 7.11E-03 | - |
| R01 | 5.44E-04 | 4.09E-03 | 4.63E-03 |
| R02 | 1.02E-03 | 4.34E-03 | 5.35E-03 |
| R03 | 1.03E-03 | 5.30E-03 | 6.33E-03 |
| R04 | 2.87E-04 | 6.64E-03 | 6.93E-03 |
| R05 | 4.32E-04 | 7.58E-03 | 8.01E-03 |
| R06 | 9.15E-04 | 3.42E-03 | 4.34E-03 |
| R07 | 1.32E-03 | 5.31E-03 | 6.63E-03 |
| R08 | 9.96E-04 | 3.92E-03 | 4.92E-03 |
| R09 | 6.22E-04 | 3.58E-03 | 4.20E-03 |
| R10 | 9.96E-04 | 3.65E-03 | 4.65E-03 |
| R11 | 1.04E-03 | 3.77E-03 | 4.81E-03 |
| R12 | 4.62E-04 | 4.42E-03 | 4.88E-03 |
| E01 | 7.77E-04 | 2.81E-03 | 3.59E-03 |
| E02 | 7.30E-04 | 4.41E-03 | 5.14E-03 |
| E03 | 7.98E-04 | 2.52E-03 | 3.32E-03 |
| E04 | 6.63E-04 | 2.08E-03 | 2.75E-03 |
| E05 | 4.66E-05 | 3.58E-03 | 3.63E-03 |
| E06 | 1.36E-03 | 2.24E-03 | 3.60E-03 |
| E07 | 8.63E-04 | 2.13E-03 | 2.99E-03 |
| E08 | 5.67E-04 | 6.09E-03 | 6.66E-03 |
| E09 | 1.15E-03 | 3.31E-03 | 4.47E-03 |
| E10 | 6.48E-04 | 2.40E-03 | 3.04E-03 |
| E11 | 6.48E-04 | 3.01E-03 | 3.66E-03 |
| K01 | 1.30E-03 | 3.64E-03 | 4.94E-03 |
| K02 | 1.53E-03 | 2.50E-03 | 4.02E-03 |
| K03 | 1.36E-03 | 3.02E-03 | 4.38E-03 |
| K04 | 1.08E-03 | 4.36E-03 | 5.44E-03 |
| K05 | 1.43E-03 | 3.01E-03 | 4.44E-03 |
| K06 | 1.47E-03 | 2.95E-03 | 4.42E-03 |
| K07 | 1.32E-03 | 1.42E-02 | 1.56E-02 |
| K08 | 2.23E-03 | 6.21E-03 | 8.44E-03 |
| K09 | 1.67E-03 | 2.95E-03 | 4.61E-03 |
| K10 | 1.88E-03 | 5.22E-03 | 7.10E-03 |
| K11 | 2.00E-03 | 1.32E-03 | 3.32E-03 |
| K12 | 2.02E-03 | 2.22E-03 | 4.24E-03 |
| K13 | 1.45E-03 | 2.46E-03 | 3.92E-03 |
| K14 | 1.58E-03 | 7.44E-03 | 9.02E-03 |
| K15 | 1.48E-03 | 4.32E-03 | 5.80E-03 |
| K16 | 1.44E-03 | 3.48E-03 | 4.92E-03 |
| K17 | 2.50E-03 | 5.65E-03 | 8.15E-03 |
| K18 | 3.67E-03 | 4.24E-03 | 7.91E-03 |
| K19 | 2.02E-03 | 3.20E-03 | 5.23E-03 |
| K20 | 1.73E-03 | 2.78E-03 | 4.51E-03 |
| K21 | 2.01E-03 | 2.94E-03 | 4.95E-03 |
| K22 | 1.62E-03 | 2.24E-03 | 3.85E-03 |
| A05 | 1.99E-03 | 2.55E-03 | 4.54E-03 |
| A06 | 1.99E-03 | 2.44E-03 | 4.43E-03 |
| A07 | 1.45E-03 | 3.79E-03 | 5.24E-03 |
| A08 | 1.54E-03 | 2.85E-03 | 4.39E-03 |
| Lower quartile | 7.98E-04 | 2.80E-03 | 4.22E-03 |
| Median | 1.30E-03 | 3.63E-03 | 4.82E-03 |
| Upper quartile | 1.58E-03 | 5.21E-03 | 6.35E-03 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 16.** Results of cases for ADPe

| | kg Sb eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.25E-04 | 6.79E-05 | 2.93E-04 |
| Enf02 | 2.01E-04 | 5.34E-05 | 2.54E-04 |
| Enf03 | 1.90E-04 | 3.02E-04 | 4.92E-04 |
| Enf04 | 1.89E-04 | 9.71E-05 | 2.86E-04 |
| Enf05 | 2.12E-04 | 8.54E-05 | 2.97E-04 |
| Enf06 | 2.12E-04 | 5.09E-05 | 2.63E-04 |
| Enf07 | 3.14E-07 | 6.80E-05 | 6.84E-05 |
| Enf08 | 2.13E-04 | 5.40E-05 | 2.67E-04 |
| Enf09 | 1.06E-04 | 5.11E-05 | 1.57E-04 |
| Enf10 | 2.06E-04 | 4.89E-05 | 2.55E-04 |
| Enf11 | - | 2.44E-04 | - |
| R01 | 1.23E-07 | 1.49E-04 | 1.49E-04 |
| R02 | 2.12E-04 | 2.71E-04 | 4.83E-04 |
| R03 | 1.84E-04 | 2.29E-04 | 4.13E-04 |
| R04 | 2.31E-04 | 1.69E-04 | 4.00E-04 |
| R05 | 2.60E-04 | 1.80E-04 | 4.41E-04 |
| R06 | 1.60E-04 | 1.63E-04 | 3.23E-04 |
| R07 | 2.00E-04 | 5.09E-05 | 2.51E-04 |
| R08 | 1.96E-04 | 7.10E-05 | 2.67E-04 |
| R09 | 2.05E-04 | 1.17E-04 | 3.22E-04 |
| R10 | 1.96E-04 | 5.69E-05 | 2.53E-04 |
| R11 | 2.11E-04 | 7.28E-05 | 2.84E-04 |
| R12 | 3.93E-04 | 2.10E-04 | 6.03E-04 |
| E01 | 1.43E-04 | 1.10E-04 | 2.53E-04 |
| E02 | 1.45E-04 | 6.29E-05 | 2.08E-04 |
| E03 | 1.83E-04 | 7.22E-05 | 2.55E-04 |
| E04 | 1.71E-04 | 7.99E-05 | 2.51E-04 |
| E05 | 1.15E-04 | 1.34E-04 | 2.49E-04 |
| E06 | 2.12E-04 | 5.96E-04 | 8.08E-04 |
| E07 | 1.43E-04 | 1.62E-04 | 3.05E-04 |
| E08 | 1.87E-04 | 2.36E-04 | 4.23E-04 |
| E09 | 1.65E-04 | 7.85E-05 | 2.43E-04 |
| E10 | 1.62E-04 | 6.64E-05 | 2.28E-04 |
| E11 | 1.62E-04 | 5.76E-05 | 2.19E-04 |
| K01 | 1.66E-04 | 3.22E-04 | 4.88E-04 |
| K02 | 1.26E-04 | 1.10E-04 | 2.36E-04 |
| K03 | 1.13E-04 | 8.18E-05 | 1.95E-04 |
| K04 | 1.11E-04 | 3.27E+00 | 3.27E+00 |
| K05 | 1.32E-04 | 2.85E-04 | 4.17E-04 |
| K06 | 9.34E-05 | 1.72E-04 | 2.65E-04 |
| K07 | 1.41E-04 | 1.06E-04 | 2.47E-04 |
| K08 | 1.56E-04 | 1.67E-04 | 3.24E-04 |
| K09 | 1.11E-04 | 2.29E-04 | 3.39E-04 |
| K10 | 1.23E-04 | 2.39E-04 | 3.62E-04 |
| K11 | 5.51E-05 | 3.67E-05 | 9.19E-05 |
| K12 | 1.65E-04 | 1.23E-04 | 2.87E-04 |
| K13 | 1.11E-04 | 1.03E-04 | 2.14E-04 |
| K14 | 1.05E-04 | 6.95E-05 | 1.75E-04 |
| K15 | 1.49E-04 | 7.96E-05 | 2.28E-04 |
| K16 | 9.80E-05 | 9.48E-05 | 1.93E-04 |
| K17 | 1.43E-04 | 9.46E-05 | 2.38E-04 |
| K18 | 8.28E-07 | 7.54E-05 | 7.62E-05 |
| K19 | 1.25E-04 | 1.83E-04 | 3.08E-04 |
| K20 | 1.18E-04 | 1.06E-04 | 2.24E-04 |
| K21 | 1.35E-04 | 9.09E-05 | 2.26E-04 |
| K22 | 1.09E-04 | 1.92E-04 | 3.01E-04 |
| A05 | 1.88E-04 | 2.81E-04 | 4.69E-04 |
| A06 | 1.88E-04 | 2.81E-04 | 4.69E-04 |
| A07 | 1.46E-04 | 7.20E-05 | 2.18E-04 |
| A08 | 1.44E-04 | 9.25E-05 | 2.37E-04 |
| Lower quartile | 1.18E-04 | 7.20E-05 | 2.29E-04 |
| Median | 1.60E-04 | 1.05E-04 | 2.64E-04 |
| Upper quartile | 1.96E-04 | 1.91E-04 | 3.40E-04 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 17.** Results of cases for ADPf

| | MJ/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.87E+01 | 5.96E+01 | 8.83E+01 |
| Enf02 | 2.48E+01 | 8.21E+01 | 1.07E+02 |
| Enf03 | 2.21E+01 | 7.21E+01 | 9.42E+01 |
| Enf04 | 2.80E+01 | 8.03E+01 | 1.08E+02 |
| Enf05 | 2.59E+01 | 4.15E+01 | 6.74E+01 |
| Enf06 | 2.59E+01 | 9.14E+01 | 1.17E+02 |
| Enf07 | 5.48E+00 | 8.73E+01 | 9.28E+01 |
| Enf08 | 2.70E+01 | 9.91E+01 | 1.26E+02 |
| Enf09 | 1.37E+01 | 7.46E+01 | 8.83E+01 |
| Enf10 | 2.53E+01 | 9.49E+01 | 1.20E+02 |
| Enf11 | - | 9.71E+01 | - |
| R01 | 2.15E+00 | 8.43E+01 | 8.64E+01 |
| R02 | 2.59E+01 | 8.24E+01 | 1.08E+02 |
| R03 | 2.31E+01 | 9.45E+01 | 1.18E+02 |
| R04 | 2.51E+01 | 1.09E+02 | 1.34E+02 |
| R05 | 2.86E+01 | 1.19E+02 | 1.47E+02 |
| R06 | 2.02E+01 | 4.52E+01 | 6.53E+01 |
| R07 | 2.59E+01 | 7.26E+01 | 9.85E+01 |
| R08 | 2.42E+01 | 7.25E+01 | 9.67E+01 |
| R09 | 2.37E+01 | 6.73E+01 | 9.09E+01 |
| R10 | 2.42E+01 | 6.44E+01 | 8.86E+01 |
| R11 | 2.59E+01 | 7.29E+01 | 9.88E+01 |
| R12 | 4.25E+01 | 6.21E+01 | 1.05E+02 |
| E01 | 1.78E+01 | 6.43E+01 | 8.21E+01 |
| E02 | 1.79E+01 | 6.26E+01 | 8.04E+01 |
| E03 | 2.21E+01 | 5.04E+01 | 7.24E+01 |
| E04 | 2.03E+01 | 5.81E+01 | 7.85E+01 |
| E05 | 1.21E+01 | 7.12E+01 | 8.33E+01 |
| E06 | 2.72E+01 | 8.95E+01 | 1.17E+02 |
| E07 | 1.82E+01 | 5.84E+01 | 7.66E+01 |
| E08 | 2.16E+01 | 8.42E+01 | 1.06E+02 |
| E09 | 2.16E+01 | 6.33E+01 | 8.48E+01 |
| E10 | 1.93E+01 | 6.68E+01 | 8.61E+01 |
| E11 | 1.93E+01 | 8.90E+01 | 1.08E+02 |
| K01 | 2.23E+01 | 6.79E+01 | 9.02E+01 |
| K02 | 1.90E+01 | 4.58E+01 | 6.48E+01 |
| K03 | 1.71E+01 | 7.86E+01 | 9.57E+01 |
| K04 | 1.57E+01 | 6.06E+01 | 7.63E+01 |
| K05 | 1.93E+01 | 9.03E+01 | 1.10E+02 |
| K06 | 1.54E+01 | 6.48E+01 | 8.02E+01 |
| K07 | 1.98E+01 | 1.02E+02 | 1.22E+02 |
| K08 | 2.49E+01 | 9.74E+01 | 1.22E+02 |
| K09 | 1.80E+01 | 7.33E+01 | 9.13E+01 |
| K10 | 2.01E+01 | 1.15E+02 | 1.36E+02 |
| K11 | 1.36E+01 | 4.44E+01 | 5.80E+01 |
| K12 | 2.50E+01 | 6.14E+01 | 8.64E+01 |
| K13 | 1.72E+01 | 4.35E+01 | 6.06E+01 |
| K14 | 1.71E+01 | 7.95E+01 | 9.66E+01 |
| K15 | 2.12E+01 | 5.92E+01 | 8.04E+01 |
| K16 | 1.58E+01 | 6.00E+01 | 7.58E+01 |
| K17 | 2.46E+01 | 7.00E+01 | 9.46E+01 |
| K18 | 1.45E+01 | 8.56E+01 | 1.00E+02 |
| K19 | 2.09E+01 | 5.61E+01 | 7.69E+01 |
| K20 | 1.90E+01 | 8.25E+01 | 1.02E+02 |
| K21 | 2.18E+01 | 5.41E+01 | 7.59E+01 |
| K22 | 1.76E+01 | 5.50E+01 | 7.26E+01 |
| A05 | 2.72E+01 | 7.18E+01 | 9.90E+01 |
| A06 | 2.72E+01 | 7.17E+01 | 9.89E+01 |
| A07 | 2.08E+01 | 9.48E+01 | 1.16E+02 |
| A08 | 2.10E+01 | 6.91E+01 | 9.00E+01 |
| Lower quartile | 1.79E+01 | 6.09E+01 | 8.05E+01 |
| Median | 2.12E+01 | 7.21E+01 | 9.29E+01 |
| Upper quartile | 2.51E+01 | 8.70E+01 | 1.08E+02 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 18.** Results of cases for PEtot

| | kWh/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.36E+01 | 2.47E+01 | 4.84E+01 |
| Enf02 | 1.91E+01 | 3.41E+01 | 5.32E+01 |
| Enf03 | 1.49E+01 | 3.69E+01 | 5.17E+01 |
| Enf04 | 2.89E+01 | 3.31E+01 | 6.21E+01 |
| Enf05 | 1.95E+01 | 3.41E+01 | 5.36E+01 |
| Enf06 | 1.95E+01 | 3.50E+01 | 5.44E+01 |
| Enf07 | 1.30E+01 | 3.86E+01 | 5.16E+01 |
| Enf08 | 2.18E+01 | 4.11E+01 | 6.29E+01 |
| Enf09 | 1.14E+01 | 3.82E+01 | 4.95E+01 |
| Enf10 | 1.93E+01 | 3.53E+01 | 5.46E+01 |
| Enf11 | - | 4.64E+01 | - |
| R01 | 5.08E+00 | 3.22E+01 | 3.73E+01 |
| R02 | 1.95E+01 | 3.63E+01 | 5.58E+01 |
| R03 | 1.83E+01 | 3.31E+01 | 5.14E+01 |
| R04 | 1.36E+01 | 3.92E+01 | 5.28E+01 |
| R05 | 1.63E+01 | 4.58E+01 | 6.22E+01 |
| R06 | 1.61E+01 | 2.87E+01 | 4.48E+01 |
| R07 | 2.18E+01 | 2.86E+01 | 5.04E+01 |
| R08 | 1.85E+01 | 2.74E+01 | 4.59E+01 |
| R09 | 1.55E+01 | 3.64E+01 | 5.19E+01 |
| R10 | 1.85E+01 | 4.78E+01 | 6.64E+01 |
| R11 | 1.97E+01 | 3.64E+01 | 5.61E+01 |
| R12 | 2.28E+01 | 3.06E+01 | 5.34E+01 |
| E01 | 1.40E+01 | 2.41E+01 | 3.81E+01 |
| E02 | 1.36E+01 | 2.19E+01 | 3.56E+01 |
| E03 | 1.61E+01 | 1.73E+01 | 3.34E+01 |
| E04 | 1.43E+01 | 2.28E+01 | 3.71E+01 |
| E05 | 5.85E+00 | 2.55E+01 | 3.14E+01 |
| E06 | 2.26E+01 | 3.32E+01 | 5.58E+01 |
| E07 | 1.48E+01 | 3.66E+01 | 5.14E+01 |
| E08 | 1.41E+01 | 2.94E+01 | 4.35E+01 |
| E09 | 1.85E+01 | 2.12E+01 | 3.98E+01 |
| E10 | 1.37E+01 | 2.41E+01 | 3.78E+01 |
| E11 | 1.37E+01 | 3.25E+01 | 4.62E+01 |
| K01 | 2.00E+01 | 2.48E+01 | 4.48E+01 |
| K02 | 2.02E+01 | 1.96E+01 | 3.98E+01 |
| K03 | 1.80E+01 | 2.66E+01 | 4.46E+01 |
| K04 | 1.53E+01 | 2.04E+01 | 3.57E+01 |
| K05 | 1.96E+01 | 3.48E+01 | 5.44E+01 |
| K06 | 1.81E+01 | 2.29E+01 | 4.10E+01 |
| K07 | 1.89E+01 | 3.40E+01 | 5.29E+01 |
| K08 | 2.82E+01 | 3.62E+01 | 6.44E+01 |
| K09 | 2.08E+01 | 2.71E+01 | 4.79E+01 |
| K10 | 2.33E+01 | 3.96E+01 | 6.29E+01 |
| K11 | 2.13E+01 | 1.64E+01 | 3.77E+01 |
| K12 | 2.66E+01 | 2.02E+01 | 4.68E+01 |
| K13 | 1.88E+01 | 1.66E+01 | 3.54E+01 |
| K14 | 1.97E+01 | 2.63E+01 | 4.60E+01 |
| K15 | 2.08E+01 | 2.04E+01 | 4.13E+01 |
| K16 | 1.81E+01 | 2.22E+01 | 4.03E+01 |
| K17 | 3.00E+01 | 2.69E+01 | 5.69E+01 |
| K18 | 3.42E+01 | 3.12E+01 | 6.55E+01 |
| K19 | 2.48E+01 | 2.27E+01 | 4.75E+01 |
| K20 | 2.17E+01 | 2.76E+01 | 4.93E+01 |
| K21 | 2.51E+01 | 1.87E+01 | 4.38E+01 |
| K22 | 2.02E+01 | 2.04E+01 | 4.07E+01 |
| A05 | 2.74E+01 | 3.00E+01 | 5.74E+01 |
| A06 | 2.74E+01 | 3.32E+01 | 6.06E+01 |
| A07 | 2.04E+01 | 3.72E+01 | 5.76E+01 |
| A08 | 2.12E+01 | 2.41E+01 | 4.53E+01 |
| Lower quartile | 1.55E+01 | 2.33E+01 | 4.11E+01 |
| Median | 1.95E+01 | 2.98E+01 | 4.94E+01 |
| Upper quartile | 2.18E+01 | 3.61E+01 | 5.47E+01 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 19.** Results of cases for Sek

| | kWh/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 4.20E-01 | 7.81E-01 | 1.20E+00 |
| Enf02 | 2.72E-01 | 7.94E-01 | 1.07E+00 |
| Enf03 | 8.67E-02 | 1.82E-01 | 2.69E-01 |
| Enf04 | 8.28E-01 | 6.88E-01 | 1.52E+00 |
| Enf05 | 2.48E-01 | 3.23E-01 | 5.70E-01 |
| Enf06 | 2.48E-01 | 6.59E-01 | 9.07E-01 |
| Enf07 | 6.79E-01 | 1.06E+00 | 1.74E+00 |
| Enf08 | 3.69E-01 | 1.01E+00 | 1.38E+00 |
| Enf09 | 2.08E-01 | 5.67E-01 | 7.75E-01 |
| Enf10 | 2.60E-01 | 1.02E+00 | 1.28E+00 |
| Enf11 | - | 1.06E+00 | - |
| R01 | 2.66E-01 | 7.74E-01 | 1.04E+00 |
| R02 | 2.48E-01 | 4.55E-01 | 7.03E-01 |
| R03 | 2.88E-01 | 7.59E-01 | 1.05E+00 |
| R04 | -1.31E-01 | 1.61E+00 | 1.48E+00 |
| R05 | -9.43E-02 | 1.28E+00 | 1.19E+00 |
| R06 | 2.60E-01 | 5.69E-01 | 8.29E-01 |
| R07 | 4.12E-01 | 2.28E-01 | 6.39E-01 |
| R08 | 2.57E-01 | 1.53E+00 | 1.78E+00 |
| R09 | 6.35E-02 | 5.86E-01 | 6.49E-01 |
| R10 | 2.57E-01 | 5.52E-01 | 8.08E-01 |
| R11 | 2.61E-01 | 9.05E-01 | 1.17E+00 |
| R12 | -2.35E-01 | 8.65E-01 | 6.30E-01 |
| E01 | 2.12E-01 | 1.74E+00 | 1.95E+00 |
| E02 | 1.87E-01 | 1.88E+00 | 2.07E+00 |
| E03 | 1.76E-01 | 2.08E+00 | 2.25E+00 |
| E04 | 1.23E-01 | 2.02E+00 | 2.15E+00 |
| E05 | -1.12E-01 | 2.80E+00 | 2.69E+00 |
| E06 | 4.15E-01 | 1.41E+00 | 1.82E+00 |
| E07 | 2.54E-01 | 6.95E-01 | 9.50E-01 |
| E08 | 5.78E-02 | 1.76E+00 | 1.82E+00 |
| E09 | 3.71E-01 | 1.43E+00 | 1.80E+00 |
| E10 | 1.27E-01 | 2.37E+00 | 2.50E+00 |
| E11 | 1.27E-01 | 1.93E+00 | 2.06E+00 |
| K01 | 4.43E-01 | 1.13E+00 | 1.57E+00 |
| K02 | 5.99E-01 | 2.25E+00 | 2.85E+00 |
| K03 | 5.32E-01 | 1.76E+00 | 2.29E+00 |
| K04 | 3.98E-01 | 1.58E+00 | 1.98E+00 |
| K05 | 5.45E-01 | 1.39E+00 | 1.94E+00 |
| K06 | 6.10E-01 | 1.09E+00 | 1.70E+00 |
| K07 | 4.78E-01 | 2.25E+00 | 2.73E+00 |
| K08 | 9.09E-01 | 7.96E-01 | 1.71E+00 |
| K09 | 6.85E-01 | 1.62E+00 | 2.31E+00 |
| K10 | 7.73E-01 | 1.71E+00 | 2.48E+00 |
| K11 | 9.14E-01 | 1.62E+00 | 2.54E+00 |
| K12 | 7.93E-01 | 1.17E+00 | 1.97E+00 |
| K13 | 5.80E-01 | 1.06E+00 | 1.64E+00 |
| K14 | 6.49E-01 | 1.45E+00 | 2.10E+00 |
| K15 | 5.50E-01 | 1.67E+00 | 2.22E+00 |
| K16 | 5.90E-01 | 1.40E+00 | 1.99E+00 |
| K17 | 1.05E+00 | 1.36E+00 | 2.42E+00 |
| K18 | 1.79E+00 | 2.82E+00 | 4.61E+00 |
| K19 | 8.44E-01 | 2.12E+00 | 2.97E+00 |
| K20 | 7.08E-01 | 2.21E+00 | 2.91E+00 |
| K21 | 8.26E-01 | 1.92E+00 | 2.75E+00 |
| K22 | 6.64E-01 | 1.28E+00 | 1.94E+00 |
| A05 | 7.51E-01 | 5.69E-01 | 1.32E+00 |
| A06 | 7.51E-01 | 4.29E-01 | 1.18E+00 |
| A07 | 5.35E-01 | 1.47E+00 | 2.01E+00 |
| A08 | 5.84E-01 | 1.73E+00 | 2.32E+00 |
| Lower quartile | 2.48E-01 | 7.76E-01 | 1.17E+00 |
| Median | 4.12E-01 | 1.32E+00 | 1.80E+00 |
| Upper quartile | 6.64E-01 | 1.74E+00 | 2.25E+00 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

# ANNEX V: DETAILED LCA RESULTS WITH 80-YEAR REFERENCE STUDY PERIOD

Tables 20 to 28 present the environmental impacts for all modules of the 60 case buildings with an 80-year reference study period as well as for all categories of environmental impact included in LCAbyg version 4.0 (beta):

- Global Warming Potential (GWP, kg $CO_2$ equivalent)
- Depletion Potential of the Stratospheric Ozone Layer (ODP, in kg R11 eq)
- Acidification Potential (AP in kg $SO_2$ eq)
- Eutrophication Potential (EP, in kg $PO_4$ eq)
- Formation Potential of Tropospheric Ozone Photochemical Oxidants (POCP, in kg ethylene eq)
- Abiotic Depletion Potential for Non-fossil Resources (ADPe, in SP eq)
- Abiotic Depletion Potential for Fossil Resources (ADPf, in MJ)
- Total Use of Primary Energy (PEtot, in MJ or kWh)
- Use of Renewable Secondary Fuels (SEK, in MJ or kWh)

**TABLE 20.** Results of cases for GWP

| | kg $CO_2$ eq/m$^2$/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.82E+00 | 4.95E+00 | 7.77E+00 |
| Enf02 | 2.45E+00 | 5.19E+00 | 7.64E+00 |
| Enf03 | 2.21E+00 | 4.56E+00 | 6.76E+00 |
| Enf04 | 2.67E+00 | 6.26E+00 | 8.94E+00 |
| Enf05 | 2.56E+00 | 3.11E+00 | 5.67E+00 |
| Enf06 | 2.56E+00 | 5.82E+00 | 8.38E+00 |
| Enf07 | 4.40E-01 | 6.61E+00 | 7.05E+00 |
| Enf08 | 2.65E+00 | 8.54E+00 | 1.12E+01 |
| Enf09 | 1.34E+00 | 5.53E+00 | 6.86E+00 |
| Enf10 | 2.50E+00 | 6.76E+00 | 9.26E+00 |
| Enf11 | - | 7.30E+00 | - |
| R01 | 1.72E-01 | 6.47E+00 | 6.64E+00 |
| R02 | 2.56E+00 | 6.37E+00 | 8.93E+00 |
| R03 | 2.27E+00 | 6.72E+00 | 8.99E+00 |
| R04 | 2.54E+00 | 9.06E+00 | 1.16E+01 |
| R05 | 2.89E+00 | 9.50E+00 | 1.24E+01 |
| R06 | 1.98E+00 | 3.60E+00 | 5.59E+00 |
| R07 | 2.53E+00 | 5.42E+00 | 7.95E+00 |
| R08 | 2.39E+00 | 5.79E+00 | 8.17E+00 |
| R09 | 2.37E+00 | 5.28E+00 | 7.65E+00 |
| R10 | 2.39E+00 | 5.09E+00 | 7.48E+00 |
| R11 | 2.56E+00 | 5.26E+00 | 7.82E+00 |
| R12 | 4.30E+00 | 4.44E+00 | 8.75E+00 |
| E01 | 1.76E+00 | 5.04E+00 | 6.79E+00 |
| E02 | 1.76E+00 | 5.11E+00 | 6.87E+00 |
| E03 | 2.19E+00 | 4.80E+00 | 6.99E+00 |
| E04 | 2.02E+00 | 5.52E+00 | 7.54E+00 |
| E05 | 1.23E+00 | 7.15E+00 | 8.38E+00 |
| E06 | 2.67E+00 | 7.33E+00 | 1.00E+01 |
| E07 | 1.78E+00 | 3.80E+00 | 5.58E+00 |
| E08 | 2.16E+00 | 6.85E+00 | 9.01E+00 |
| E09 | 2.11E+00 | 5.04E+00 | 7.15E+00 |
| E10 | 1.92E+00 | 6.26E+00 | 8.18E+00 |
| E11 | 1.92E+00 | 6.33E+00 | 8.24E+00 |
| K01 | 2.17E+00 | 6.14E+00 | 8.30E+00 |
| K02 | 1.81E+00 | 4.24E+00 | 6.06E+00 |
| K03 | 1.63E+00 | 6.95E+00 | 8.57E+00 |
| K04 | 1.51E+00 | 5.33E+00 | 6.85E+00 |
| K05 | 1.85E+00 | 7.31E+00 | 9.16E+00 |
| K06 | 1.45E+00 | 5.11E+00 | 6.56E+00 |
| K07 | 1.91E+00 | 8.32E+00 | 1.02E+01 |
| K08 | 2.36E+00 | 7.90E+00 | 1.03E+01 |
| K09 | 1.69E+00 | 6.04E+00 | 7.73E+00 |
| K10 | 1.89E+00 | 9.27E+00 | 1.12E+01 |
| K11 | 1.21E+00 | 3.71E+00 | 4.92E+00 |
| K12 | 2.38E+00 | 5.28E+00 | 7.66E+00 |
| K13 | 1.63E+00 | 4.13E+00 | 5.77E+00 |
| K14 | 1.61E+00 | 6.37E+00 | 7.98E+00 |
| K15 | 2.04E+00 | 4.80E+00 | 6.84E+00 |
| K16 | 1.49E+00 | 5.56E+00 | 7.05E+00 |
| K17 | 2.30E+00 | 5.88E+00 | 8.18E+00 |
| K18 | 1.16E+00 | 7.88E+00 | 9.04E+00 |
| K19 | 1.96E+00 | 5.30E+00 | 7.26E+00 |
| K20 | 1.79E+00 | 6.86E+00 | 8.65E+00 |
| K21 | 2.06E+00 | 4.76E+00 | 6.81E+00 |
| K22 | 1.66E+00 | 4.60E+00 | 6.26E+00 |
| A05 | 2.61E+00 | 5.66E+00 | 8.27E+00 |
| A06 | 2.61E+00 | 5.48E+00 | 8.10E+00 |
| A07 | 2.00E+00 | 7.24E+00 | 9.25E+00 |
| A08 | 2.01E+00 | 6.05E+00 | 8.06E+00 |
| Lower quartile | 1.76E+00 | 5.06E+00 | 6.86E+00 |
| Median | 2.04E+00 | 5.72E+00 | 7.95E+00 |
| Upper quartile | 2.50E+00 | 6.83E+00 | 8.93E+00 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 21.** Results of cases for ODP

| | kg R11 eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.29E-10 | 2.60E-08 | 2.62E-08 |
| Enf02 | 2.01E-10 | 3.23E-08 | 3.25E-08 |
| Enf03 | 1.85E-10 | 7.65E-08 | 7.67E-08 |
| Enf04 | 2.08E-10 | 4.38E-08 | 4.40E-08 |
| Enf05 | 2.11E-10 | 7.15E-08 | 7.17E-08 |
| Enf06 | 2.11E-10 | 4.36E-08 | 4.38E-08 |
| Enf07 | 2.22E-11 | 1.22E-07 | 1.22E-07 |
| Enf08 | 2.16E-10 | 1.99E-07 | 1.99E-07 |
| Enf09 | 1.09E-10 | 5.21E-08 | 5.22E-08 |
| Enf10 | 2.06E-10 | 1.48E-07 | 1.48E-07 |
| Enf11 | - | 1.12E-07 | - |
| R01 | 8.70E-12 | 8.67E-09 | 8.68E-09 |
| R02 | 2.11E-10 | 2.26E-08 | 2.28E-08 |
| R03 | 1.86E-10 | 6.89E-09 | 7.08E-09 |
| R04 | 2.18E-10 | 1.35E-08 | 1.37E-08 |
| R05 | 2.47E-10 | 1.53E-08 | 1.56E-08 |
| R06 | 1.62E-10 | 2.88E-08 | 2.90E-08 |
| R07 | 2.05E-10 | 2.77E-08 | 2.79E-08 |
| R08 | 1.96E-10 | 9.47E-08 | 9.49E-08 |
| R09 | 1.99E-10 | 4.09E-08 | 4.11E-08 |
| R10 | 1.96E-10 | 8.26E-08 | 8.28E-08 |
| R11 | 2.11E-10 | 1.31E-07 | 1.31E-07 |
| R12 | 3.69E-10 | 3.31E-08 | 3.34E-08 |
| E01 | 1.44E-10 | 1.63E-08 | 1.64E-08 |
| E02 | 1.45E-10 | 7.34E-09 | 7.48E-09 |
| E03 | 1.81E-10 | 1.21E-08 | 1.23E-08 |
| E04 | 1.68E-10 | 8.48E-09 | 8.64E-09 |
| E05 | 1.07E-10 | 1.47E-08 | 1.48E-08 |
| E06 | 2.16E-10 | 3.14E-09 | 3.36E-09 |
| E07 | 1.45E-10 | 7.38E-08 | 7.39E-08 |
| E08 | 1.81E-10 | 7.95E-09 | 8.13E-09 |
| E09 | 1.70E-10 | 6.79E-09 | 6.96E-09 |
| E10 | 1.59E-10 | 1.72E-08 | 1.74E-08 |
| E11 | 1.59E-10 | 5.32E-08 | 5.34E-08 |
| K01 | 1.73E-10 | 5.63E-09 | 5.80E-09 |
| K02 | 1.40E-10 | 7.30E-09 | 7.44E-09 |
| K03 | 1.26E-10 | 8.12E-08 | 8.13E-08 |
| K04 | 1.19E-10 | 8.04E-09 | 8.16E-09 |
| K05 | 1.44E-10 | 1.67E-08 | 1.68E-08 |
| K06 | 1.09E-10 | 7.28E-09 | 7.39E-09 |
| K07 | 1.51E-10 | 1.40E-08 | 1.42E-08 |
| K08 | 1.79E-10 | 7.89E-09 | 8.07E-09 |
| K09 | 1.28E-10 | 6.26E-09 | 6.39E-09 |
| K10 | 1.43E-10 | 1.60E-08 | 1.61E-08 |
| K11 | 8.24E-11 | 1.19E-08 | 1.20E-08 |
| K12 | 1.84E-10 | 4.16E-09 | 4.34E-09 |
| K13 | 1.25E-10 | 4.14E-09 | 4.27E-09 |
| K14 | 1.22E-10 | 9.09E-09 | 9.21E-09 |
| K15 | 1.61E-10 | 8.21E-09 | 8.37E-09 |
| K16 | 1.13E-10 | 7.37E-09 | 7.49E-09 |
| K17 | 1.71E-10 | 7.04E-09 | 7.21E-09 |
| K18 | 5.86E-11 | 5.42E-09 | 5.48E-09 |
| K19 | 1.47E-10 | 3.61E-08 | 3.62E-08 |
| K20 | 1.36E-10 | 1.57E-08 | 1.58E-08 |
| K21 | 1.56E-10 | 6.50E-09 | 6.65E-09 |
| K22 | 1.26E-10 | 5.53E-09 | 5.65E-09 |
| A05 | 2.04E-10 | 2.13E-08 | 2.15E-08 |
| A06 | 2.04E-10 | 2.04E-08 | 2.06E-08 |
| A07 | 1.58E-10 | 1.00E-08 | 1.02E-08 |
| A08 | 1.57E-10 | 7.36E-09 | 7.51E-09 |
| Lower quartile | 1.36E-10 | 7.36E-09 | 7.49E-09 |
| Median | 1.62E-10 | 1.55E-08 | 1.56E-08 |
| Upper quartile | 2.04E-10 | 4.29E-08 | 4.11E-08 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 22.** Results of cases for AP

| | kg $SO_2$ eq/m$^2$/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 1.15E-02 | 1.45E-02 | 2.60E-02 |
| Enf02 | 9.44E-03 | 1.28E-02 | 2.22E-02 |
| Enf03 | 7.52E-03 | 1.95E-02 | 2.70E-02 |
| Enf04 | 1.36E-02 | 1.27E-02 | 2.63E-02 |
| Enf05 | 9.65E-03 | 1.11E-02 | 2.08E-02 |
| Enf06 | 9.65E-03 | 1.53E-02 | 2.49E-02 |
| Enf07 | 5.62E-03 | 1.29E-02 | 1.85E-02 |
| Enf08 | 1.07E-02 | 2.44E-02 | 3.51E-02 |
| Enf09 | 5.53E-03 | 1.49E-02 | 2.04E-02 |
| Enf10 | 9.52E-03 | 1.80E-02 | 2.75E-02 |
| Enf11 | - | 2.03E-02 | - |
| R01 | 2.20E-03 | 2.24E-02 | 2.46E-02 |
| R02 | 9.65E-03 | 2.18E-02 | 3.15E-02 |
| R03 | 8.98E-03 | 1.98E-02 | 2.87E-02 |
| R04 | 7.21E-03 | 2.47E-02 | 3.19E-02 |
| R05 | 8.56E-03 | 2.42E-02 | 3.28E-02 |
| R06 | 7.88E-03 | 9.18E-03 | 1.71E-02 |
| R07 | 1.06E-02 | 1.25E-02 | 2.31E-02 |
| R08 | 9.15E-03 | 1.35E-02 | 2.26E-02 |
| R09 | 7.88E-03 | 1.39E-02 | 2.18E-02 |
| R10 | 9.15E-03 | 1.53E-02 | 2.45E-02 |
| R11 | 9.72E-03 | 1.39E-02 | 2.36E-02 |
| R12 | 1.21E-02 | 1.36E-02 | 2.57E-02 |
| E01 | 6.87E-03 | 1.28E-02 | 1.97E-02 |
| E02 | 6.74E-03 | 1.19E-02 | 1.86E-02 |
| E03 | 8.01E-03 | 1.26E-02 | 2.06E-02 |
| E04 | 7.16E-03 | 1.64E-02 | 2.36E-02 |
| E05 | 3.19E-03 | 1.51E-02 | 1.83E-02 |
| E06 | 1.10E-02 | 1.77E-02 | 2.87E-02 |
| E07 | 7.22E-03 | 1.20E-02 | 1.92E-02 |
| E08 | 7.18E-03 | 1.66E-02 | 2.38E-02 |
| E09 | 8.97E-03 | 1.12E-02 | 2.02E-02 |
| E10 | 6.85E-03 | 1.38E-02 | 2.07E-02 |
| E11 | 6.85E-03 | 1.68E-02 | 2.37E-02 |
| K01 | 9.60E-03 | 1.88E-02 | 2.84E-02 |
| K02 | 9.46E-03 | 1.02E-02 | 1.97E-02 |
| K03 | 8.45E-03 | 2.02E-02 | 2.87E-02 |
| K04 | 7.27E-03 | 1.22E-02 | 1.94E-02 |
| K05 | 9.24E-03 | 2.44E-02 | 3.36E-02 |
| K06 | 8.38E-03 | 1.38E-02 | 2.21E-02 |
| K07 | 9.01E-03 | 1.78E-02 | 2.68E-02 |
| K08 | 1.31E-02 | 2.38E-02 | 3.69E-02 |
| K09 | 9.62E-03 | 1.69E-02 | 2.65E-02 |
| K10 | 1.08E-02 | 2.37E-02 | 3.45E-02 |
| K11 | 9.52E-03 | 9.31E-03 | 1.88E-02 |
| K12 | 1.25E-02 | 1.62E-02 | 2.87E-02 |
| K13 | 8.77E-03 | 1.20E-02 | 2.08E-02 |
| K14 | 9.13E-03 | 1.34E-02 | 2.25E-02 |
| K15 | 9.87E-03 | 1.12E-02 | 2.10E-02 |
| K16 | 8.38E-03 | 1.53E-02 | 2.37E-02 |
| K17 | 1.38E-02 | 1.38E-02 | 2.76E-02 |
| K18 | 1.48E-02 | 1.95E-02 | 3.43E-02 |
| K19 | 1.14E-02 | 1.32E-02 | 2.46E-02 |
| K20 | 1.01E-02 | 2.03E-02 | 3.03E-02 |
| K21 | 1.16E-02 | 1.16E-02 | 2.32E-02 |
| K22 | 9.38E-03 | 1.24E-02 | 2.18E-02 |
| A05 | 1.29E-02 | 1.88E-02 | 3.18E-02 |
| A06 | 1.29E-02 | 1.83E-02 | 3.12E-02 |
| A07 | 9.67E-03 | 2.17E-02 | 3.14E-02 |
| A08 | 9.99E-03 | 1.66E-02 | 2.66E-02 |
| Lower quartile | 7.88E-03 | 1.27E-02 | 2.08E-02 |
| Median | 9.38E-03 | 1.52E-02 | 2.45E-02 |
| Upper quartile | 1.06E-02 | 1.93E-02 | 2.87E-02 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 23.** Results of cases for EP

| | kg $PO_4$ eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.25E-03 | 1.77E-03 | 4.02E-03 |
| Enf02 | 1.80E-03 | 1.74E-03 | 3.54E-03 |
| Enf03 | 1.36E-03 | 2.84E-03 | 4.20E-03 |
| Enf04 | 2.85E-03 | 1.82E-03 | 4.67E-03 |
| Enf05 | 1.82E-03 | 1.72E-03 | 3.54E-03 |
| Enf06 | 1.82E-03 | 2.17E-03 | 3.99E-03 |
| Enf07 | 1.37E-03 | 1.66E-03 | 3.03E-03 |
| Enf08 | 2.07E-03 | 3.12E-03 | 5.19E-03 |
| Enf09 | 1.08E-03 | 2.27E-03 | 3.36E-03 |
| Enf10 | 1.81E-03 | 2.46E-03 | 4.27E-03 |
| Enf11 | - | 2.57E-03 | - |
| R01 | 5.37E-04 | 2.25E-03 | 2.79E-03 |
| R02 | 1.82E-03 | 2.65E-03 | 4.47E-03 |
| R03 | 1.73E-03 | 1.93E-03 | 3.66E-03 |
| R04 | 1.18E-03 | 2.48E-03 | 3.66E-03 |
| R05 | 1.44E-03 | 2.47E-03 | 3.91E-03 |
| R06 | 1.52E-03 | 1.35E-03 | 2.87E-03 |
| R07 | 2.08E-03 | 1.84E-03 | 3.92E-03 |
| R08 | 1.74E-03 | 1.70E-03 | 3.44E-03 |
| R09 | 1.41E-03 | 1.98E-03 | 3.38E-03 |
| R10 | 1.74E-03 | 2.36E-03 | 4.10E-03 |
| R11 | 1.84E-03 | 1.88E-03 | 3.72E-03 |
| R12 | 1.98E-03 | 1.94E-03 | 3.92E-03 |
| E01 | 1.32E-03 | 1.50E-03 | 2.82E-03 |
| E02 | 1.28E-03 | 1.51E-03 | 2.80E-03 |
| E03 | 1.50E-03 | 1.71E-03 | 3.20E-03 |
| E04 | 1.32E-03 | 2.15E-03 | 3.47E-03 |
| E05 | 4.91E-04 | 2.02E-03 | 2.51E-03 |
| E06 | 2.16E-03 | 2.08E-03 | 4.24E-03 |
| E07 | 1.40E-03 | 1.76E-03 | 3.16E-03 |
| E08 | 1.28E-03 | 1.88E-03 | 3.16E-03 |
| E09 | 1.78E-03 | 1.44E-03 | 3.22E-03 |
| E10 | 1.27E-03 | 1.77E-03 | 3.04E-03 |
| E11 | 1.27E-03 | 1.97E-03 | 3.23E-03 |
| K01 | 1.93E-03 | 2.04E-03 | 3.97E-03 |
| K02 | 1.99E-03 | 1.30E-03 | 3.30E-03 |
| K03 | 1.78E-03 | 2.18E-03 | 3.95E-03 |
| K04 | 1.50E-03 | 1.41E-03 | 2.91E-03 |
| K05 | 1.92E-03 | 2.89E-03 | 4.82E-03 |
| K06 | 1.81E-03 | 1.49E-03 | 3.30E-03 |
| K07 | 1.84E-03 | 2.21E-03 | 4.05E-03 |
| K08 | 2.81E-03 | 3.11E-03 | 5.92E-03 |
| K09 | 2.07E-03 | 2.36E-03 | 4.44E-03 |
| K10 | 2.33E-03 | 3.12E-03 | 5.44E-03 |
| K11 | 2.19E-03 | 1.22E-03 | 3.40E-03 |
| K12 | 2.63E-03 | 2.48E-03 | 5.11E-03 |
| K13 | 1.86E-03 | 1.49E-03 | 3.35E-03 |
| K14 | 1.97E-03 | 1.81E-03 | 3.77E-03 |
| K15 | 2.04E-03 | 1.40E-03 | 3.43E-03 |
| K16 | 1.80E-03 | 2.12E-03 | 3.92E-03 |
| K17 | 3.01E-03 | 1.92E-03 | 4.94E-03 |
| K18 | 3.62E-03 | 2.36E-03 | 5.98E-03 |
| K19 | 2.48E-03 | 1.84E-03 | 4.32E-03 |
| K20 | 2.16E-03 | 3.00E-03 | 5.16E-03 |
| K21 | 2.50E-03 | 1.47E-03 | 3.98E-03 |
| K22 | 2.02E-03 | 1.56E-03 | 3.58E-03 |
| A05 | 2.69E-03 | 2.46E-03 | 5.15E-03 |
| A06 | 2.69E-03 | 2.54E-03 | 5.22E-03 |
| A07 | 1.99E-03 | 2.39E-03 | 4.38E-03 |
| A08 | 2.08E-03 | 2.19E-03 | 4.26E-03 |
| Lower quartile | 1.44E-03 | 1.71E-03 | 3.30E-03 |
| Median | 1.82E-03 | 1.97E-03 | 3.91E-03 |
| Upper quartile | 2.08E-03 | 2.38E-03 | 4.32E-03 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 24.** Results of cases for POCP

| | kg ethylene eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 1.14E-03 | 2.34E-03 | 3.48E-03 |
| Enf02 | 8.49E-04 | 2.96E-03 | 3.81E-03 |
| Enf03 | 5.22E-04 | 9.59E-04 | 1.48E-03 |
| Enf04 | 1.74E-03 | 3.69E-03 | 5.43E-03 |
| Enf05 | 8.31E-04 | 1.50E-03 | 2.33E-03 |
| Enf06 | 8.31E-04 | 3.56E-03 | 4.39E-03 |
| Enf07 | 1.12E-03 | 5.25E-03 | 6.37E-03 |
| Enf08 | 1.03E-03 | 6.06E-03 | 7.09E-03 |
| Enf09 | 5.54E-04 | 3.17E-03 | 3.72E-03 |
| Enf10 | 8.38E-04 | 4.82E-03 | 5.66E-03 |
| Enf11 | - | 5.50E-03 | - |
| R01 | 4.37E-04 | 3.13E-03 | 3.56E-03 |
| R02 | 8.31E-04 | 3.33E-03 | 4.16E-03 |
| R03 | 8.41E-04 | 3.73E-03 | 4.57E-03 |
| R04 | 2.47E-04 | 5.24E-03 | 5.48E-03 |
| R05 | 3.67E-04 | 7.14E-03 | 7.50E-03 |
| R06 | 7.47E-04 | 2.55E-03 | 3.29E-03 |
| R07 | 1.08E-03 | 3.75E-03 | 4.83E-03 |
| R08 | 8.14E-04 | 2.93E-03 | 3.75E-03 |
| R09 | 5.15E-04 | 2.83E-03 | 3.35E-03 |
| R10 | 8.14E-04 | 2.85E-03 | 3.66E-03 |
| R11 | 8.51E-04 | 3.00E-03 | 3.85E-03 |
| R12 | 4.00E-04 | 3.09E-03 | 3.49E-03 |
| E01 | 6.35E-04 | 2.30E-03 | 2.94E-03 |
| E02 | 5.97E-04 | 3.20E-03 | 3.80E-03 |
| E03 | 6.55E-04 | 2.26E-03 | 2.92E-03 |
| E04 | 5.45E-04 | 1.87E-03 | 2.42E-03 |
| E05 | 4.59E-05 | 2.75E-03 | 2.79E-03 |
| E06 | 1.11E-03 | 1.84E-03 | 2.95E-03 |
| E07 | 7.04E-04 | 1.66E-03 | 2.36E-03 |
| E08 | 4.69E-04 | 5.06E-03 | 5.53E-03 |
| E09 | 9.39E-04 | 2.36E-03 | 3.30E-03 |
| E10 | 5.32E-04 | 1.79E-03 | 2.32E-03 |
| E11 | 5.32E-04 | 2.17E-03 | 2.71E-03 |
| K01 | 1.06E-03 | 2.84E-03 | 3.90E-03 |
| K02 | 1.24E-03 | 1.79E-03 | 3.02E-03 |
| K03 | 1.10E-03 | 2.87E-03 | 3.97E-03 |
| K04 | 8.76E-04 | 4.04E-03 | 4.91E-03 |
| K05 | 1.16E-03 | 2.55E-03 | 3.70E-03 |
| K06 | 1.19E-03 | 2.43E-03 | 3.62E-03 |
| K07 | 1.07E-03 | 1.45E-02 | 1.56E-02 |
| K08 | 1.81E-03 | 5.98E-03 | 7.78E-03 |
| K09 | 1.35E-03 | 2.34E-03 | 3.69E-03 |
| K10 | 1.52E-03 | 5.25E-03 | 6.77E-03 |
| K11 | 1.61E-03 | 9.47E-04 | 2.56E-03 |
| K12 | 1.63E-03 | 1.80E-03 | 3.43E-03 |
| K13 | 1.18E-03 | 1.99E-03 | 3.16E-03 |
| K14 | 1.28E-03 | 6.50E-03 | 7.78E-03 |
| K15 | 1.20E-03 | 3.27E-03 | 4.47E-03 |
| K16 | 1.17E-03 | 3.05E-03 | 4.22E-03 |
| K17 | 2.01E-03 | 5.11E-03 | 7.12E-03 |
| K18 | 2.94E-03 | 3.12E-03 | 6.06E-03 |
| K19 | 1.64E-03 | 2.87E-03 | 4.50E-03 |
| K20 | 1.40E-03 | 2.33E-03 | 3.73E-03 |
| K21 | 1.63E-03 | 2.10E-03 | 3.73E-03 |
| K22 | 1.31E-03 | 1.64E-03 | 2.95E-03 |
| A05 | 1.61E-03 | 2.20E-03 | 3.81E-03 |
| A06 | 1.61E-03 | 2.14E-03 | 3.75E-03 |
| A07 | 1.17E-03 | 2.69E-03 | 3.86E-03 |
| A08 | 1.25E-03 | 2.19E-03 | 3.43E-03 |
| Lower quartile | 6.55E-04 | 2.19E-03 | 3.29E-03 |
| Median | 1.06E-03 | 2.86E-03 | 3.75E-03 |
| Upper quartile | 1.28E-03 | 3.72E-03 | 4.83E-03 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 25.** Results of cases for ADPe

| | kg Sb eq/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.15E-04 | 5.19E-05 | 2.67E-04 |
| Enf02 | 1.92E-04 | 5.39E-05 | 2.46E-04 |
| Enf03 | 1.81E-04 | 2.02E-04 | 3.83E-04 |
| Enf04 | 1.81E-04 | 6.88E-05 | 2.49E-04 |
| Enf05 | 2.03E-04 | 7.19E-05 | 2.75E-04 |
| Enf06 | 2.03E-04 | 4.45E-05 | 2.47E-04 |
| Enf07 | 3.20E-07 | 6.37E-05 | 6.41E-05 |
| Enf08 | 2.03E-04 | 5.19E-05 | 2.55E-04 |
| Enf09 | 1.02E-04 | 4.26E-05 | 1.44E-04 |
| Enf10 | 1.97E-04 | 4.29E-05 | 2.40E-04 |
| Enf11 | - | 2.24E-04 | - |
| R01 | 1.25E-07 | 1.36E-04 | 1.36E-04 |
| R02 | 2.03E-04 | 2.25E-04 | 4.27E-04 |
| R03 | 1.76E-04 | 1.86E-04 | 3.62E-04 |
| R04 | 2.21E-04 | 1.66E-04 | 3.87E-04 |
| R05 | 2.49E-04 | 1.84E-04 | 4.33E-04 |
| R06 | 1.53E-04 | 1.12E-04 | 2.65E-04 |
| R07 | 1.91E-04 | 4.48E-05 | 2.36E-04 |
| R08 | 1.87E-04 | 6.40E-05 | 2.51E-04 |
| R09 | 1.96E-04 | 8.81E-05 | 2.84E-04 |
| R10 | 1.87E-04 | 5.05E-05 | 2.38E-04 |
| R11 | 2.02E-04 | 6.23E-05 | 2.64E-04 |
| R12 | 3.76E-04 | 1.71E-04 | 5.47E-04 |
| E01 | 1.37E-04 | 7.97E-05 | 2.16E-04 |
| E02 | 1.38E-04 | 5.67E-05 | 1.95E-04 |
| E03 | 1.75E-04 | 6.16E-05 | 2.36E-04 |
| E04 | 1.64E-04 | 7.17E-05 | 2.36E-04 |
| E05 | 1.10E-04 | 1.12E-04 | 2.22E-04 |
| E06 | 2.02E-04 | 3.94E-04 | 5.96E-04 |
| E07 | 1.37E-04 | 1.14E-04 | 2.50E-04 |
| E08 | 1.79E-04 | 1.81E-04 | 3.59E-04 |
| E09 | 1.58E-04 | 6.67E-05 | 2.24E-04 |
| E10 | 1.55E-04 | 6.66E-05 | 2.21E-04 |
| E11 | 1.55E-04 | 4.81E-05 | 2.03E-04 |
| K01 | 1.59E-04 | 3.43E-04 | 5.02E-04 |
| K02 | 1.20E-04 | 7.85E-05 | 1.99E-04 |
| K03 | 1.08E-04 | 7.35E-05 | 1.82E-04 |
| K04 | 1.06E-04 | 4.09E+00 | 4.09E+00 |
| K05 | 1.26E-04 | 2.60E-04 | 3.86E-04 |
| K06 | 8.93E-05 | 1.25E-04 | 2.14E-04 |
| K07 | 1.35E-04 | 9.57E-05 | 2.31E-04 |
| K08 | 1.49E-04 | 1.54E-04 | 3.04E-04 |
| K09 | 1.06E-04 | 1.67E-04 | 2.72E-04 |
| K10 | 1.18E-04 | 1.95E-04 | 3.13E-04 |
| K11 | 5.27E-05 | 3.04E-05 | 8.32E-05 |
| K12 | 1.58E-04 | 8.72E-05 | 2.45E-04 |
| K13 | 1.06E-04 | 9.22E-05 | 1.98E-04 |
| K14 | 1.01E-04 | 5.90E-05 | 1.60E-04 |
| K15 | 1.42E-04 | 7.09E-05 | 2.13E-04 |
| K16 | 9.36E-05 | 8.44E-05 | 1.78E-04 |
| K17 | 1.37E-04 | 8.01E-05 | 2.17E-04 |
| K18 | 8.44E-07 | 5.82E-05 | 5.91E-05 |
| K19 | 1.19E-04 | 2.09E-04 | 3.28E-04 |
| K20 | 1.13E-04 | 9.28E-05 | 2.06E-04 |
| K21 | 1.29E-04 | 7.97E-05 | 2.08E-04 |
| K22 | 1.04E-04 | 1.62E-04 | 2.66E-04 |
| A05 | 1.79E-04 | 2.60E-04 | 4.40E-04 |
| A06 | 1.79E-04 | 2.60E-04 | 4.40E-04 |
| A07 | 1.40E-04 | 6.62E-05 | 2.06E-04 |
| A08 | 1.38E-04 | 8.83E-05 | 2.26E-04 |
| Lower quartile | 1.13E-04 | 6.26E-05 | 2.08E-04 |
| Median | 1.53E-04 | 8.58E-05 | 2.45E-04 |
| Upper quartile | 1.87E-04 | 1.70E-04 | 3.13E-04 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the ‘All modules’ column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 26.** Results of cases for ADPf

| | MJ/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.59E+01 | 5.04E+01 | 7.63E+01 |
| Enf02 | 2.24E+01 | 6.11E+01 | 8.35E+01 |
| Enf03 | 2.01E+01 | 5.63E+01 | 7.64E+01 |
| Enf04 | 2.47E+01 | 6.79E+01 | 9.26E+01 |
| Enf05 | 2.35E+01 | 3.58E+01 | 5.93E+01 |
| Enf06 | 2.35E+01 | 6.65E+01 | 9.00E+01 |
| Enf07 | 4.34E+00 | 8.09E+01 | 8.52E+01 |
| Enf08 | 2.43E+01 | 9.34E+01 | 1.18E+02 |
| Enf09 | 1.23E+01 | 6.38E+01 | 7.61E+01 |
| Enf10 | 2.29E+01 | 7.67E+01 | 9.96E+01 |
| Enf11 | - | 8.00E+01 | - |
| R01 | 1.70E+00 | 7.02E+01 | 7.19E+01 |
| R02 | 2.35E+01 | 7.17E+01 | 9.52E+01 |
| R03 | 2.08E+01 | 8.03E+01 | 1.01E+02 |
| R04 | 2.30E+01 | 9.67E+01 | 1.20E+02 |
| R05 | 2.63E+01 | 1.11E+02 | 1.37E+02 |
| R06 | 1.82E+01 | 3.80E+01 | 5.61E+01 |
| R07 | 2.33E+01 | 6.84E+01 | 9.17E+01 |
| R08 | 2.19E+01 | 5.94E+01 | 8.13E+01 |
| R09 | 2.16E+01 | 6.02E+01 | 8.17E+01 |
| R10 | 2.19E+01 | 5.69E+01 | 7.88E+01 |
| R11 | 2.34E+01 | 5.74E+01 | 8.08E+01 |
| R12 | 3.91E+01 | 4.83E+01 | 8.74E+01 |
| E01 | 1.61E+01 | 4.88E+01 | 6.49E+01 |
| E02 | 1.61E+01 | 4.77E+01 | 6.39E+01 |
| E03 | 2.00E+01 | 4.19E+01 | 6.19E+01 |
| E04 | 1.85E+01 | 4.95E+01 | 6.80E+01 |
| E05 | 1.11E+01 | 6.45E+01 | 7.57E+01 |
| E06 | 2.45E+01 | 7.50E+01 | 9.95E+01 |
| E07 | 1.64E+01 | 4.73E+01 | 6.37E+01 |
| E08 | 1.97E+01 | 7.20E+01 | 9.16E+01 |
| E09 | 1.94E+01 | 5.09E+01 | 7.03E+01 |
| E10 | 1.75E+01 | 5.86E+01 | 7.61E+01 |
| E11 | 1.75E+01 | 6.59E+01 | 8.34E+01 |
| K01 | 1.99E+01 | 6.15E+01 | 8.14E+01 |
| K02 | 1.68E+01 | 3.48E+01 | 5.16E+01 |
| K03 | 1.51E+01 | 7.30E+01 | 8.80E+01 |
| K04 | 1.40E+01 | 5.24E+01 | 6.63E+01 |
| K05 | 1.71E+01 | 7.79E+01 | 9.50E+01 |
| K06 | 1.35E+01 | 5.68E+01 | 7.04E+01 |
| K07 | 1.76E+01 | 8.91E+01 | 1.07E+02 |
| K08 | 2.19E+01 | 9.03E+01 | 1.12E+02 |
| K09 | 1.58E+01 | 5.98E+01 | 7.55E+01 |
| K10 | 1.76E+01 | 1.05E+02 | 1.23E+02 |
| K11 | 1.15E+01 | 3.31E+01 | 4.46E+01 |
| K12 | 2.20E+01 | 5.36E+01 | 7.56E+01 |
| K13 | 1.51E+01 | 3.94E+01 | 5.45E+01 |
| K14 | 1.50E+01 | 6.88E+01 | 8.38E+01 |
| K15 | 1.88E+01 | 4.61E+01 | 6.49E+01 |
| K16 | 1.39E+01 | 5.34E+01 | 6.72E+01 |
| K17 | 2.15E+01 | 6.31E+01 | 8.45E+01 |
| K18 | 1.14E+01 | 7.06E+01 | 8.20E+01 |
| K19 | 1.82E+01 | 4.75E+01 | 6.58E+01 |
| K20 | 1.67E+01 | 7.28E+01 | 8.95E+01 |
| K21 | 1.91E+01 | 4.27E+01 | 6.18E+01 |
| K22 | 1.54E+01 | 4.67E+01 | 6.22E+01 |
| A05 | 2.41E+01 | 6.35E+01 | 8.77E+01 |
| A06 | 2.41E+01 | 6.56E+01 | 8.97E+01 |
| A07 | 1.85E+01 | 6.98E+01 | 8.83E+01 |
| A08 | 1.86E+01 | 5.85E+01 | 7.71E+01 |
| Lower quartile | 1.61E+01 | 4.98E+01 | 6.72E+01 |
| Median | 1.88E+01 | 6.13E+01 | 8.13E+01 |
| Upper quartile | 2.29E+01 | 7.19E+01 | 9.00E+01 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 27.** Results of cases for PEtot

| | kWh/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 2.15E+01 | 1.99E+01 | 4.15E+01 |
| Enf02 | 1.74E+01 | 2.44E+01 | 4.18E+01 |
| Enf03 | 1.33E+01 | 2.99E+01 | 4.32E+01 |
| Enf04 | 2.68E+01 | 2.87E+01 | 5.54E+01 |
| Enf05 | 1.76E+01 | 2.50E+01 | 4.26E+01 |
| Enf06 | 1.76E+01 | 2.68E+01 | 4.44E+01 |
| Enf07 | 1.24E+01 | 3.78E+01 | 5.01E+01 |
| Enf08 | 1.99E+01 | 3.68E+01 | 5.67E+01 |
| Enf09 | 1.04E+01 | 3.05E+01 | 4.08E+01 |
| Enf10 | 1.75E+01 | 2.91E+01 | 4.66E+01 |
| Enf11 | - | 3.80E+01 | - |
| R01 | 4.85E+00 | 2.73E+01 | 3.22E+01 |
| R02 | 1.76E+01 | 2.97E+01 | 4.73E+01 |
| R03 | 1.66E+01 | 2.78E+01 | 4.44E+01 |
| R04 | 1.19E+01 | 3.55E+01 | 4.75E+01 |
| R05 | 1.44E+01 | 4.35E+01 | 5.79E+01 |
| R06 | 1.46E+01 | 2.40E+01 | 3.86E+01 |
| R07 | 1.99E+01 | 2.61E+01 | 4.59E+01 |
| R08 | 1.68E+01 | 2.24E+01 | 3.92E+01 |
| R09 | 1.38E+01 | 3.06E+01 | 4.45E+01 |
| R10 | 1.68E+01 | 4.13E+01 | 5.81E+01 |
| R11 | 1.78E+01 | 2.74E+01 | 4.52E+01 |
| R12 | 2.00E+01 | 2.36E+01 | 4.36E+01 |
| E01 | 1.27E+01 | 1.87E+01 | 3.14E+01 |
| E02 | 1.24E+01 | 1.69E+01 | 2.92E+01 |
| E03 | 1.45E+01 | 1.46E+01 | 2.91E+01 |
| E04 | 1.28E+01 | 2.01E+01 | 3.29E+01 |
| E05 | 5.07E+00 | 2.30E+01 | 2.81E+01 |
| E06 | 2.07E+01 | 2.68E+01 | 4.74E+01 |
| E07 | 1.35E+01 | 2.84E+01 | 4.19E+01 |
| E08 | 1.26E+01 | 2.56E+01 | 3.82E+01 |
| E09 | 1.69E+01 | 1.72E+01 | 3.42E+01 |
| E10 | 1.23E+01 | 2.08E+01 | 3.31E+01 |
| E11 | 1.23E+01 | 2.42E+01 | 3.65E+01 |
| K01 | 1.83E+01 | 2.27E+01 | 4.11E+01 |
| K02 | 1.87E+01 | 1.49E+01 | 3.36E+01 |
| K03 | 1.67E+01 | 2.45E+01 | 4.12E+01 |
| K04 | 1.41E+01 | 1.78E+01 | 3.19E+01 |
| K05 | 1.81E+01 | 2.95E+01 | 4.76E+01 |
| K06 | 1.69E+01 | 2.03E+01 | 3.72E+01 |
| K07 | 1.74E+01 | 2.95E+01 | 4.70E+01 |
| K08 | 2.62E+01 | 3.48E+01 | 6.10E+01 |
| K09 | 1.93E+01 | 2.25E+01 | 4.18E+01 |
| K10 | 2.17E+01 | 3.52E+01 | 5.69E+01 |
| K11 | 2.00E+01 | 1.20E+01 | 3.20E+01 |
| K12 | 2.46E+01 | 1.74E+01 | 4.21E+01 |
| K13 | 1.74E+01 | 1.57E+01 | 3.32E+01 |
| K14 | 1.83E+01 | 2.27E+01 | 4.11E+01 |
| K15 | 1.92E+01 | 1.58E+01 | 3.50E+01 |
| K16 | 1.68E+01 | 2.01E+01 | 3.69E+01 |
| K17 | 2.80E+01 | 2.45E+01 | 5.25E+01 |
| K18 | 3.27E+01 | 2.60E+01 | 5.87E+01 |
| K19 | 2.31E+01 | 2.01E+01 | 4.32E+01 |
| K20 | 2.02E+01 | 2.43E+01 | 4.45E+01 |
| K21 | 2.34E+01 | 1.47E+01 | 3.80E+01 |
| K22 | 1.88E+01 | 1.72E+01 | 3.60E+01 |
| A05 | 2.53E+01 | 2.59E+01 | 5.12E+01 |
| A06 | 2.53E+01 | 3.05E+01 | 5.57E+01 |
| A07 | 1.88E+01 | 2.74E+01 | 4.62E+01 |
| A08 | 1.95E+01 | 2.04E+01 | 3.99E+01 |
| Lower quartile | 1.41E+01 | 2.01E+01 | 3.65E+01 |
| Median | 1.76E+01 | 2.45E+01 | 4.19E+01 |
| Upper quartile | 2.00E+01 | 2.94E+01 | 4.73E+01 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

**TABLE 28.** Results of cases for Sek

| | kWh/m²/year | | |
|---|---|---|---|
| | **Operation B6** | **Materials A1-3, B4, C3-4** | **All modules A1-3, B4, B6, C3-4** |
| Enf01 | 4.12E-01 | 5.04E-01 | 9.17E-01 |
| Enf02 | 2.68E-01 | 4.96E-01 | 7.64E-01 |
| Enf03 | 8.58E-02 | 1.21E-01 | 2.07E-01 |
| Enf04 | 8.13E-01 | 4.30E-01 | 1.24E+00 |
| Enf05 | 2.44E-01 | 2.27E-01 | 4.71E-01 |
| Enf06 | 2.44E-01 | 4.56E-01 | 7.00E-01 |
| Enf07 | 6.66E-01 | 6.74E-01 | 1.34E+00 |
| Enf08 | 3.63E-01 | 6.39E-01 | 1.00E+00 |
| Enf09 | 2.04E-01 | 3.60E-01 | 5.64E-01 |
| Enf10 | 2.55E-01 | 6.47E-01 | 9.02E-01 |
| Enf11 | - | 6.66E-01 | - |
| R01 | 2.61E-01 | 4.88E-01 | 7.49E-01 |
| R02 | 2.44E-01 | 3.06E-01 | 5.50E-01 |
| R03 | 2.83E-01 | 4.78E-01 | 7.61E-01 |
| R04 | -1.28E-01 | 1.05E+00 | 9.24E-01 |
| R05 | -9.14E-02 | 8.38E-01 | 7.46E-01 |
| R06 | 2.55E-01 | 3.57E-01 | 6.12E-01 |
| R07 | 4.05E-01 | 1.51E-01 | 5.56E-01 |
| R08 | 2.53E-01 | 9.54E-01 | 1.21E+00 |
| R09 | 6.31E-02 | 3.72E-01 | 4.35E-01 |
| R10 | 2.53E-01 | 3.67E-01 | 6.20E-01 |
| R11 | 2.57E-01 | 5.70E-01 | 8.27E-01 |
| R12 | -2.29E-01 | 5.55E-01 | 3.26E-01 |
| E01 | 2.09E-01 | 1.10E+00 | 1.31E+00 |
| E02 | 1.84E-01 | 1.18E+00 | 1.37E+00 |
| E03 | 1.73E-01 | 1.32E+00 | 1.49E+00 |
| E04 | 1.21E-01 | 1.28E+00 | 1.40E+00 |
| E05 | -1.09E-01 | 1.76E+00 | 1.65E+00 |
| E06 | 4.08E-01 | 8.92E-01 | 1.30E+00 |
| E07 | 2.50E-01 | 4.41E-01 | 6.91E-01 |
| E08 | 5.75E-02 | 1.10E+00 | 1.16E+00 |
| E09 | 3.64E-01 | 8.95E-01 | 1.26E+00 |
| E10 | 1.25E-01 | 1.48E+00 | 1.61E+00 |
| E11 | 1.25E-01 | 1.69E+00 | 1.81E+00 |
| K01 | 4.35E-01 | 7.21E-01 | 1.16E+00 |
| K02 | 5.88E-01 | 1.40E+00 | 1.99E+00 |
| K03 | 5.22E-01 | 1.12E+00 | 1.64E+00 |
| K04 | 3.91E-01 | 9.90E-01 | 1.38E+00 |
| K05 | 5.35E-01 | 8.94E-01 | 1.43E+00 |
| K06 | 5.98E-01 | 6.81E-01 | 1.28E+00 |
| K07 | 4.69E-01 | 1.42E+00 | 1.89E+00 |
| K08 | 8.92E-01 | 4.99E-01 | 1.39E+00 |
| K09 | 6.72E-01 | 1.02E+00 | 1.69E+00 |
| K10 | 7.59E-01 | 1.09E+00 | 1.85E+00 |
| K11 | 8.96E-01 | 1.02E+00 | 1.91E+00 |
| K12 | 7.78E-01 | 7.40E-01 | 1.52E+00 |
| K13 | 5.70E-01 | 6.68E-01 | 1.24E+00 |
| K14 | 6.36E-01 | 9.09E-01 | 1.54E+00 |
| K15 | 5.40E-01 | 1.04E+00 | 1.58E+00 |
| K16 | 5.79E-01 | 8.74E-01 | 1.45E+00 |
| K17 | 1.03E+00 | 8.56E-01 | 1.89E+00 |
| K18 | 1.76E+00 | 1.77E+00 | 3.53E+00 |
| K19 | 8.28E-01 | 1.34E+00 | 2.17E+00 |
| K20 | 6.95E-01 | 1.41E+00 | 2.10E+00 |
| K21 | 8.10E-01 | 1.20E+00 | 2.01E+00 |
| K22 | 6.51E-01 | 8.00E-01 | 1.45E+00 |
| A05 | 7.37E-01 | 3.57E-01 | 1.09E+00 |
| A06 | 7.37E-01 | 2.69E-01 | 1.01E+00 |
| A07 | 5.26E-01 | 9.24E-01 | 1.45E+00 |
| A08 | 5.73E-01 | 1.10E+00 | 1.67E+00 |
| Lower quartile | 2.44E-01 | 4.90E-01 | 7.64E-01 |
| Median | 4.05E-01 | 8.47E-01 | 1.30E+00 |
| Upper quartile | 6.51E-01 | 1.10E+00 | 1.61E+00 |

Note that the median value has been calculated on the basis of different parts of the results. Therefore, the 'All modules' column will not be the exact sum of the medians for the input phases. The results have been adjusted for missing data on technical installations (see section 3.2).

*Whole life carbon assessment of 60 buildings - Possibilities to develop benchmark values for LCA of buildings* assesses the hitherto largest number of building cases collected in Denmark with regard to GWP. As part of the objective to reduce global greenhouse gas emissions, in recent years there has been great focus in the building and construction sector on reducing the climate footprint of buildings. In this respect, life cycle assessment (LCA) is a key tool in documenting the climate footprint of buildings as a consequence of manufacturing and disposing of building materials as well as energy use at the operation stage. This report collects and prepares LCAs for 60 Danish building cases within the building types: detached house, terraced house, apartment building, offices and other buildings. These 60 building cases provide a basis to generate knowledge about the GWP of buildings. Furthermore, benchmark values have been developed for the climate footprint of buildings, and these can be used as benchmarks for future construction projects. The report shows a clear potential to shift the building and construction sector towards a lower climate footprint and to accommodate sustainable development in society.

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